GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

July 29, 1966

National Aeronautics and Space Administration
Kennedy Space Center, Florida 32899

Attn: Mr. Charles C. Hays, PRO-73

Subject: Monthly Progress Report No. 1, covering period 27 June 1966 to 27 July 1966, Project A-955, Contract No. NAS10-3895, "Study of Saturn Launch Complex Signal Distribution Improvement," Control No. MR 60236(F).

Gentlemen:

During this first month of the Contract, work was initiated on studying methods and procedures for improving the signal distribution system for the Saturn Launch Complex.

A visit was made by project personnel to Kennedy Space Center on 12 July 1966, to discuss technical aspects of the problem. The existing signal distribution system for launch sites on Cape Kennedy was reviewed in addition to discussing requirements for the signal distribution system for the Saturn Complex.

The initial phase of the study has been established and is now under way. In this phase four possible transmission systems will be examined to determine their capability to provide data links of the type required. Two of these systems are wired (twisted pair and coaxial cable) and two are wireless (millimeter waves and radio at more nominal frequencies, such as UHF or microwave frequencies). This initial effort will consist of theoretical study of the capability of each type of system together with a preliminary survey of equipment availability. The object of this initial phase is to rapidly acquire data that will indicate the comparative merits of the four systems. The system or systems which appear best will then be considered in more detail.

For each of the systems, consideration is being given to more than just the transmission medium itself; also being considered is the method of coupling the signals in and out of the system. For the wireless systems and coaxial cable, the wide bandwidth available would permit various schemes to be used, for example, frequency multiplex or pulse coding. At present, the use of frequency multiplex appears most promising and this method will be considered first. The use of pulse coding has the disadvantage that special provisions would be necessary so that if two events occurred simultaneously, correct indication of both would be transmitted.

For the twisted pair, the main question being investigated is whether or not a suitable system can be devised using twisted pair that will deliver the event signals within the time limit of 1 millisecond. A theoretical analysis of the characteristics of twisted pair has been initiated and is still being pursued. Various possibilities for putting the signal into the pair and detecting it will be considered.

Effort is also underway on both the nominal frequency radio system and the millimeter wave system. The initial work involves considering overall system concept and search for data on state-of-the-art, availability, and cost of the various components, such as transmitters, receivers, multiplexers, etc.

During the coming month, these lines of investigation will continue as all are in very early stages right now. Consideration is presently being given to initiating experimental work in two areas; (1) FM multiplexing a 35 GHz system and (2) building a laboratory analog of a twisted pair cable to allow experimental investigation. It is anticipated that these studies will be on a small scale and relatively inexpensive. Both of these lines of investigation will probably be undertaken during the coming month.

Respectfully submitted:

R. D. Wetherington
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

September 1, 1966

National Aeronautics and Space Administration
Kennedy Space Center, Florida 32899

Attn: Mr. Charles C. Hays, PRO-73

Subject: Monthly Progress Report No. 2, covering period 27 July 1966 to 27 August 1966, Project A-955, Contract No. NAS10-3895, "Study of Saturn Launch Complex Signal Distribution Improvement," Control No. MR 60236(F).

Gentlemen:

During the past month, work has continued on investigating the four data transmission systems (twisted pair cable, coaxial cable, millimeter wave radio, and radio at more nominal frequencies). Some effort has been expended on each of the four systems.

Theoretical analysis of the response of twisted pair cable (based on the characteristics of Type 19DNB cable) to an input DC step indicated that the pulse rise time at the end of a 20 mile line should be about 1.3 milliseconds. To further check this result, a 40 section R-C analog of a 20 mile line was constructed and tested. Measurements of the pulse rise time at the end of the line corresponded very closely to the predicted value.

To investigate why delays of the order of 50 milliseconds had been encountered in the data transmission system presently used, a Potter-Brumfield Type KCP-11 relay (similar to that used to terminate the line) was obtained and tested. When this relay was driven directly from a 28 volt source, closure time was measured to be 15 milliseconds. Closure time was also measured for other voltages, and the closure time increased as the voltage was reduced. At an input of 21 volts, closure time exceeded 70 milliseconds and was somewhat erratic, varying from about 70 to over 100 milliseconds. When the voltage was reduced slightly below 21 volts, the relay failed to close.

This relay was then operated through a 7 mile section of the analog line. With a driving voltage of 28 volts, closure time was measured to be 25 milliseconds. The steady state voltage at the relay terminals was 21.2 volts after transient effects subsided. The voltage at the terminals rose above 21.2 volts for several milliseconds after pulse build-up before the coil began to conduct fully.

These tests indicate that the delay time experienced on the existing transmission system was due primarily to relay effects rather than line effects. With about 400-500 Ω resistance in the line and 2500 Ω in the relay coil, the voltage at the terminals would be reduced to about 80% of the input voltage. This reduced voltage would increase the closure time above the 15 milliseconds required when driving it directly from the voltage source. Quite possibly the closure time could be improved considerably simply by raising the driving voltage enough to counter-act the voltage drop in the line. For a seven mile line, a driving voltage of about 35 volts would be required to provide 28 volts at the relay terminals in the steady state.

Tests were also run on the analog line using an electronic switch instead of a relay. A transistorized Schmitt trigger with an adjustable threshold level was constructed and operated through the line. The threshold was adjusted so that the trigger fired during pulse rise rather than on the peak of the pulse. Operated through the 20 mile line, reliable operation was obtained with a response time of 150 μsec. Using only a seven mile section of the line, response times down to 30 μsec were obtained. These times were obtained with the threshold level of the Schmitt trigger set quite low. It is probable that on an actual line a higher threshold (giving a longer response time) would be necessary since the threshold must be higher than the noise level on the line. However, response times well within the required time of one millisecond appear feasible.

The above method has the disadvantage of requiring one line for each event to be monitored. Some thought has been given to trying to transmit several events on one line by frequency multiplexing a carrier frequency and using a receiver at the termination. By using a receiver, line losses up to about 100 db could be tolerated. Whether or not this method is practical depends on the line losses that will exist at frequencies which are suitable for carriers.

Study of other systems has also progressed, particularly for the millimeter wave system. The availability and cost of components for a system operating at 35 GHz have been surveyed, and the RF portion of a 20 link system designed. Estimated cost of the RF components is approximately $95,000. This figure does not include installation costs or the cost of multiplexing and decoding equipment.

A brief survey of coaxial cable characteristics reveals that the attenuation on the smaller cables which are available at reasonable cost is excessive. Installation of a coaxial cable system would require either the use of a large expensive cable, or the use of repeater stations at intervals along the line.

For either a radio system or a coaxial cable system, some form of multiplexing will be required. Thus far, suitable multiplexing equipment available as off-the-shelf components has not been found. Most readily available multiplexing equipment is designed for voice communications and feature channel bandwidths of about 3 kHz. A wider channel width would be desirable for the event distribution system.

Ideas currently exist for constructing a suitable multiplexing system that will meet the requirements and be relatively inexpensive. A laboratory experiment for testing this scheme is currently underway.

During the next month, the lines of investigation underway will be continued. The multiplexing experiment should be completed during the month. Studies of the twisted-pair line will be continued. Provided suitable arrangements can be made, a visit will be made to Kennedy Space Center in order to perform tests on actual twisted pair lines. Tests currently planned are (1) measuring the response time of the Schmitt trigger when driven through a line, (2) measurement of the RMS noise level on the lines, and (3) measurement of the line attenuation at frequencies suitable for modulated sub-carriers (of the order of 50 or 100 kHz).

Respectfully submitted:

R. D. Wetherington
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

30 September 1966

National Aeronautics and Space Administration
Kennedy Space Center, Florida 32899

Attn: Mr. Charles C. Hays, PRO-73

Subject: Monthly Progress Report No. 3, covering period 27 August 1966 to 27 September 1966, Project A-955, Contract No. NAS10-3895, "Study of Saturn Launch Complex Signal Distribution Improvement," Control No. MR 60236(F).

Gentlemen:

During the past month, effort on the Saturn Launch Complex signal distribution improvement study has been directed primarily toward experimental investigation of both wired and wireless systems.

To investigate a scheme for frequency multiplexing signals on a radio transmitter, a two-channel multiplexing unit was constructed and tested in the laboratory. Since the information to be transmitted in the event distribution system is binary in character (either a "yes" or a "no"), the multiplexing system required can be much simpler than those usually used for voice communication. A system in which a sub-carrier is modulated on the transmitter to signal an event will suffice; no modulation of the sub-carrier is required.

The two-channel test system consisted of two sub-carrier oscillators (tuned to 38 kHz and 104 kHz for the tests), two gating circuits, two bandpass filters, a summing network, and a baseband amplifier. In operation, the oscillators are operated continuously and each oscillator's output is passed through a gate to the summing network. The gates are controlled by the "events". The gate is normally closed, but opens when the monitored event occurs. Each gate is followed by a bandpass filter centered at the sub-carrier frequency of that channel to prevent any spurious frequencies from reaching the summing network. The network combines all sub-carriers being passed by the gates and its output is passed through a baseband amplifier which frequency modulates the transmitter klystron.

The complete two-channel system was implemented in the laboratory using an X-band transmitter and receiver. The X-band system was chosen because the components were readily available; the same modulation scheme could be applied to a 35 GHz system.

Tests indicated that the signal build-up time was about 100 μsec for each signal. This build-up time was due primarily to lag in the filters; the propagation time was negligible, since the transmission path was only a few feet. About 30 db of isolation between the two channels was achieved.

In studies on twisted-pair cable, the 40 section analog of a 20 mile line was modified during the month by adding inductors to each section. This modified line is a much better analog of type 19 DNB cable. Measurements on the line show that the build-up time for DC pulses is approximately the same as measured on the RC line. However, the modified line shows much less loss for frequencies above 3 kHz.

These laboratory tests were augmented with tests made at Kennedy Space Center on actual twisted pair lines. A visit was made to KSC by R. W. Moss, W. B. Warren, and R. D. Wetherington on September 20-21, to make these measurements. Tests run included the build-up of DC pulses, transmission characteristics of the line for frequencies up to 200 kHz, and the transmission of event markers by using electronic indicating devices at the termination of the line. Measurements on these lines agreed well with the laboratory measurements on the analog lines. These measurements show that a suitable event distribution system can be built around twisted pair lines.

Work during the coming month will be directed toward the detail design and cost estimation of various systems. Work thus far has shown that both wired and wireless systems are capable of meeting the specified requirements; however, neither system is available as a complete off-the-shelf system. Many of the components needed in both are readily available, however. The system design effort will include selection of particular types of components, and acquisition of cost and procurement data.

Respectfully submitted:

R. D. Wetherington
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

H-955

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

4 November 1966

National Aeronautics and Space Administration
Kennedy Space Center, Florida 32899

Attn: Mr. Charles C. Hays, PRO-73

Subj: Monthly Progress Report No. 4, covering period 27 September 1966 to 27 October 1966, Project A-955, Contract No. NAS10-3895, "Study of Saturn Launch Complex Signal Distribution Improvement," Control No. MR 60236(F).

Gentlemen:

Work on the Saturn Launch Complex signal distribution improvement study has centered on initial planning of various systems.

Following the laboratory experiments conducted during the previous month on multiplexing an X-band transmitter, plans in block diagram form for a radio link system capable of handling 20 channels of information (20 events) have been drawn. Also, estimates of the cost of the various components needed for the system have been made. It is estimated that the component cost for building a 20 channel multiplexing unit for the transmitter will be approximately $8,200. The cost for building a single demultiplexing unit for one receiving station would be $6,200. Thus, a system consisting of one transmitter and 20 receivers would cost $132,000 for the multiplexing equipment.

The multiplexing equipment could be used in conjunction with various types of radio equipment. If it were used with the 35 GHz system, which was planned earlier in this study, the total component cost for the signal distribution system would be $226,650.

A similar line of effort has been followed in further studies of a distribution system based on twisted-pair cable. Study and analysis of the data obtained on twisted-pair cable from measurements made at Kennedy Space Center on 20-21 September 1966, indicate that implementation of a signal distribution system using twisted pair cable is feasible. A block diagram of such a system has been constructed and an effort is under way to procure component cost data. Obtaining such cost data will require time since some components, particularly filters, which are needed for this system are not available as standard off-the-shelf items. In addition, it is not possible at this time to specify the characteristics needed in the filters with certainty, since such characteristics as cross-over points and steepness of roll-off could only be determined with additional experimental work which is beyond the scope of this study. However, selectivity curves representing our best estimate of the necessary characteristics have been drawn, and cost estimates based on these specifications will be requested.

As a summary of the overall status of the investigation to date, our studies show that a signal distribution system meeting the specifications could be implemented either as a wired or a wireless system; also, that frequency multiplexing can be used with either system. However, neither is available as a complete off-the-shelf system, and would have to be assembled from components. The needed components exist, for the most part, either as off-the-shelf items or can be readily procured on special order. A few minor components may have to be constructed, but these should present no unusual difficulty. However, in constructing any system involving assembling many components, numerous unforeseen problems usually arise and must be eliminated. In short, it would be highly desirable that a proto-type be constructed prior to the implementation on an operational basis of either system.

During the coming month, work will continue on the design of these systems and procurement of cost data.

Respectfully submitted;

R. D. Wetherington
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

2 December 1966

National Aeronautics and Space Administration
Kennedy Space Center, Florida 32899

Attn: Mr. Charles C. Hays, PRO-73

Subj: Monthly Progress Report No. 5, covering period 27 October 1966 to 27 November 1966, Project A-955, Contract No. NAS10-3895, "Study of Saturn Launch Complex Signal Distribution Improvement," Control No. MR 60236(F).

Gentlemen:

During the past month, work has continued on the planning and cost analysis of event distribution systems, with most of the effort devoted to a system built around twisted-pair cable.

The planning of a twisted-pair cable system has been hindered somewhat by a lack of information on the use of such lines in the manner contemplated. Most of the information available on such lines deal with the transmission of audio tones and methods of minimizing distortion. In the system being planned, the information will be transmitted at frequencies above the nominal 3 dB passband limit of about 3 kHz; also, the major objective is to achieve minimum time of transmission rather than low distortion. The lack of information on such use has not prohibited the planning of a system, but has required that some parameters be chosen very conservatively.

The system will use frequency multiplex to transmit several events over a single line. Each event channel will have a bandwidth of 4 kHz, and the channel center frequencies will be spaced 8 kHz apart with the lowest center frequency at 7 kHz. Placing the lowest channel at 7 kHz rather than at a lower frequency will accomplish two things; (1) it should reduce the possibility of interference between the signals and audio signals on other pairs lying in the same sheath, and (2) it avoids the low frequency region in which time delay varies greatly with frequency.

By assuming that at least 10 dB of isolation will exist between any two pairs, and that an additional 60 dB of isolation can be obtained by using common mode rejection, the maximum noise on the line should not exceed -63 dBm (assuming the maximum power level on any line is +7 dBm). For a 20 dB signal-to-noise ratio, the minimum acceptable signal at the output of the line then becomes -43 dbm. Using this figure together with attenuation vs frequency data for 19 DNB cable, it was possible to decide on the input power level required on any given channel for a given length line. Also, the number of channels that could be combined on a single line before the total input power exceeded 7 dbm was determined for various length lines. The results indicate that a five mile line could carry 25 events, a ten mile line could carry 7 events, while a 15 mile line could carry only 2 events.

Some cost data on the system components have been procured during the past month. Cost estimates of one of the major items, the 4 kHz bandpass filters for channel isolation, have not been received to date, but this problem is being pursued.

Work on the system design and cost estimation should be completed during the coming month. Also, work on a final report will be initiated during the month as it is anticipated that somewhat more than the 30 day report preparation period will be needed to complete the report.

Respectfully submitted:

R. D. Wetherington
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

FINAL REPORT

PROJECT A-955

SATURN LAUNCH COMPLEX SIGNAL DISTRIBUTION IMPROVEMENT

R. D. WETHERINGTON
R. W. MOSS
R. G. SHACKLEFORD
A. P. SHEPPARD

Contract No. NAS10-3895

27 June 1966 to 27 December 1966

Prepared for
National Aeronautics and Space Administration
John F. Kennedy Space Center
Kennedy Space Center, Florida

1966

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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FINAL REPORT

PROJECT A-955

SATURN LAUNCH COMPLEX SIGNAL DISTRIBUTION IMPROVEMENT

By

R. D. WETHERINGTON
R. W. MOSS
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A. P. SHEPPARD

CONTRACT No. NAS10-3895

27 JUNE 1966 to 27 DECEMBER 1966

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHN F. KENNEDY SPACE CENTER
KENNEDY SPACE CENTER, FLORIDA

FOREWORD

This report was prepared at the Georgia Institute of Technology Engineering Experiment Station under Contract No. NAS10-3895 with the National Aeronautics and Space Administration, John F. Kennedy Space Center, Cocoa Beach, Florida. The materials contained herein present the results of a six-month study of problems associated with distributing signals over the Saturn Launch Complex indicating that certain critical events have occurred.

The program was conducted under the general supervision of Mr. D. W. Robertson, Head, Communications Branch. Acknowledgement is made to Messrs. E. E. Donaldson, W. B. Warren, and J. R. Walsh for their able assistance and advice in carrying out this study.

Respectfully submitted:

R. D. Wetherington
Project Director

Approved:

M. W. Long, Chief
Electronics Division

ABSTRACT

During pre-launch and launch activities for Saturn vehicles, a number of asynchronous events will occur which must be signaled to several monitoring points. Indications of the occurrence of these events will be available at the launch control center, and signals indicating these occurrences must be transmitted to about 20 remote sites at distances up to 20 miles within 1 millisecond.

This study was undertaken to consider various means for transmitting these signals and to make recommendations on a system. The event signal distribution system used for previous launches was reviewed to determine the characteristics of the present system. Five different transmission systems (two radio systems, a wired system using twisted pair, a coaxial line system, and a laser beam system) were then studied and compared. The study was primarily theoretical, but a limited amount of experimental work was conducted. Also, tentative cost estimates were made on those systems which appeared most attractive. It is recommended that a system that multiplexes signals on twin-pair line be given first consideration on the basis of cost (exclusive of line costs), reliability, ease of maintenance, and flexibility.

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I. Introduction

During launch operations for space vehicles a number of critical events occur on an arbitrary time scale. Examples of such events are first-motion, lift-off, cut-off, and others. For control and monitoring of the launch operation, it is necessary that indications of these events be transmitted to launch support activities with little time delay.

In early space vehicle launches, this requirement presented no problem since few such events were monitored and the primary support activities were located in close proximity (within 2000 feet) to the launch pad. A relatively simple signal distribution system using twisted-pair cable met all requirements. Later, when the Central Instrumentation Facility (CIF) was constructed, a similar system failed to be completely satisfactory for transmitting event signals to CIF since a transmission path several miles long was involved and delays of about 30 milliseconds were experienced.

The Saturn program poses even more problems in implementing an event signal distribution system. It is anticipated that a larger number of events will be monitored (currently estimated to be 16). Also, the launch complex will be scattered over a larger area with instrument locations typically several miles away. The Saturn program thus involves the transmission of more event signals, transmission to more sites, and transmission over larger distances. The study covered by this report was directed toward methods and techniques for constructing a suitable event signal distribution system for the Saturn launch complex.

The essential elements of the problem can be summarized as follows. All event signals will either originate at the launch control center (LCC) or will be transmitted from their source to LCC by existing communications channels. For purposes of this study, then, all signals were considered to originate and be available at LCC. These signals must be distributed to about 20 remote sites. The distances to the sites are typically a few miles; most of the sites lie within ten miles of LCC, but at least one site is more remote at a distance of about 20 miles. The time for transmission of an event signal is to be less than 1 millisecond.

A number of other factors which are also pertinent to the problem are:

(1) Except for authorized transmissions, NASA currently requires radio silence in the launch complex during launch activities at all frequencies up through X-band. At present, there is not a radio channel assigned for transmitting the subject event signals.

(2) The present distribution system uses twisted-pair cable to transmit the event signals and requires one line per event. If this system were replaced by another wired system, more efficient use of the lines would be desired.

(3) The use of repeaters in a wired system is undesirable.

These factors were not regarded as necessarily restrictive to this study, but they may well influence the final choice of an event distribution system.

The particular study reported here was aimed at review and study of various methods of transmitting signals in order to determine what system or systems could be used for the event signal distribution system for the Saturn complex. As one step in carrying out this study, the existing event distribution system was reviewed and analyzed to better understand its deficiencies. The findings of this study are presented in Section II.

Following the review of the present system, several types of transmission system were investigated as possibilities for implementing an event distribution system that would meet the time requirement of 1 millisecond. In order to provide a system that would not become obsolete when and if it became necessary to monitor more events, all of these studies were made on the basis of requiring the system to transmit 30 events.

Altogether five different transmission systems, both wired and wireless, were considered. Two of these were radio systems (similar except for frequency), two were wired systems (twisted pair and coaxial cable), and the other system was a laser beam system.

In making these studies, it quickly became apparent that one of the major problems was that of multiplexing. Several inquiries to manufacturers were unsuccessful in locating suitable multiplexing equipment. Two small-scale experimental programs were then undertaken in connection with multiplexing, one to test the feasibility of a simplified multiplexer for use with radio, and the other to investigate the ability of twisted-pair cable to carry multiplexed signals. Each of these experiments is discussed along with the system to which it applies.

II. Analysis of Existing Event Distribution System

A. General

The present event distribution system at Kennedy Space Center utilizes 19 guage twisted-pair transmission lines linking a power source and electromechanical relays. When an event occurs, a step voltage is applied at the sending end of a line and this voltage subsequently closes a relay at the receiving terminal. The transmission path is about 7 miles long and the total time from event occurrence to relay closure has been found to be approximately 30 milliseconds. Since DC voltage levels are used for signaling, a twisted-pair line is required to distribute each event signal.

Initially, it was thought that the relays used to terminate the lines were fast-response relays with actuation times of 1-2 milliseconds, and that the large time delays were associated with the lines. However, preliminary calculations of theoretical line characteristics failed to reveal any reason for the large time delays observed; instead, they indicated that the transmission time on 19 guage twisted-pair cable should be small enough to permit this cable to be used for a one millisecond event distribution system. To examine this possibility and also to determine the cause of the time delays in the existing system, a broad study of the system was undertaken. Time and frequency response characteristics of the line were calculated theoretically and checked against measurements made on both laboratory models of the line and on an actual line. The operational characteristics of the type relay being used as an output device were also measured. Details of these studies are covered in the following sections.

B. Twisted-Pair Transmission Line Characteristics

Since it was desirable to verify theoretical calculations of line characteristics with measured values and since actual lines were not readily available, two analog models of twisted-pair lines were constructed for laboratory use.

A lumped parameter representation of 19 guage twisted-pair line is shown in Figure 1. The values shown for resistance, capacitance, inductance, and conductance were obtained from published data.[1] In an actual line these parameters are distributed continuously along the length of the line, but a close approximation to the line can be obtained by constructing a many-sectioned network in which the distributed parameters of a short length of the line are lumped into a single RLC section.[2] Both models were constructed with 40 sections each and represented 20 mile lines, hence, each section was built to represent one-half mile of line.

Some delay was experienced in obtaining the proper inductance coils to build a complete analog of the line. In the interim, the first model was constructed using only resistance and capacitance and is shown schematically in Figure 2. Since the distributed resistance and capacitance are the predominant low frequency parameters,[2] this model served satisfactorily for the measurement of transient response to a voltage step. Later, when the proper inductances were obtained, the 40 section analog of a 20 mile line shown in Figure 3 was constructed.

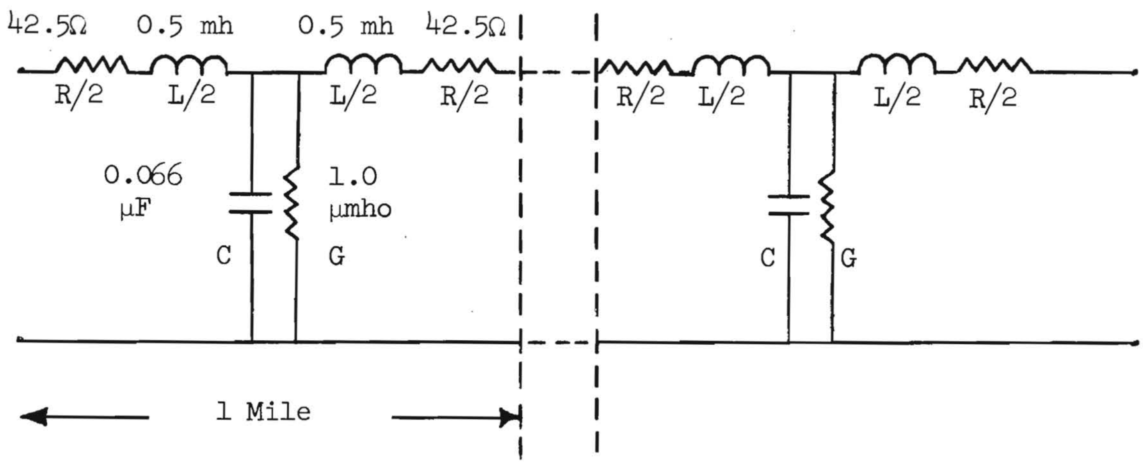


Figure 1. Lumped parameter representation of 19 guage twisted-pair line.

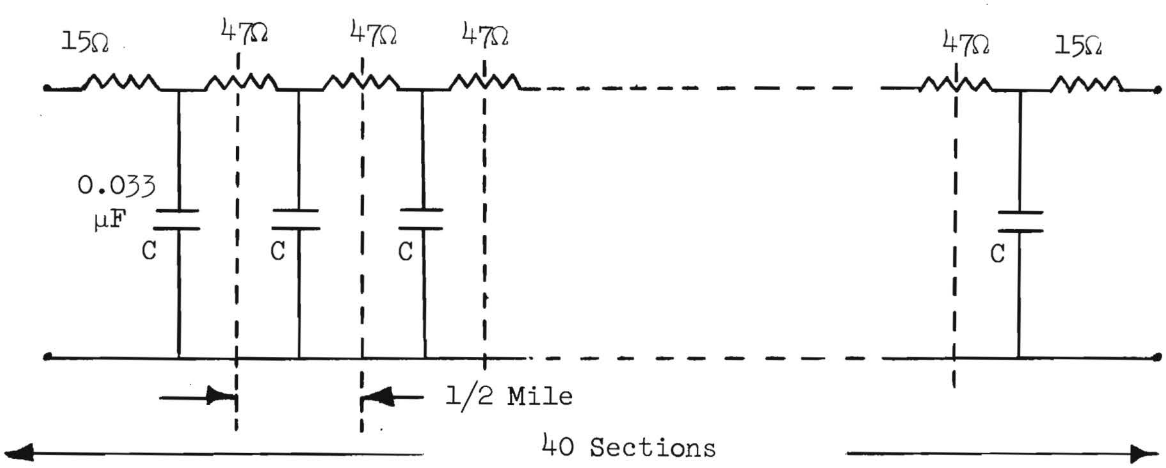


Figure 2. RC analog of twisted-pair line.

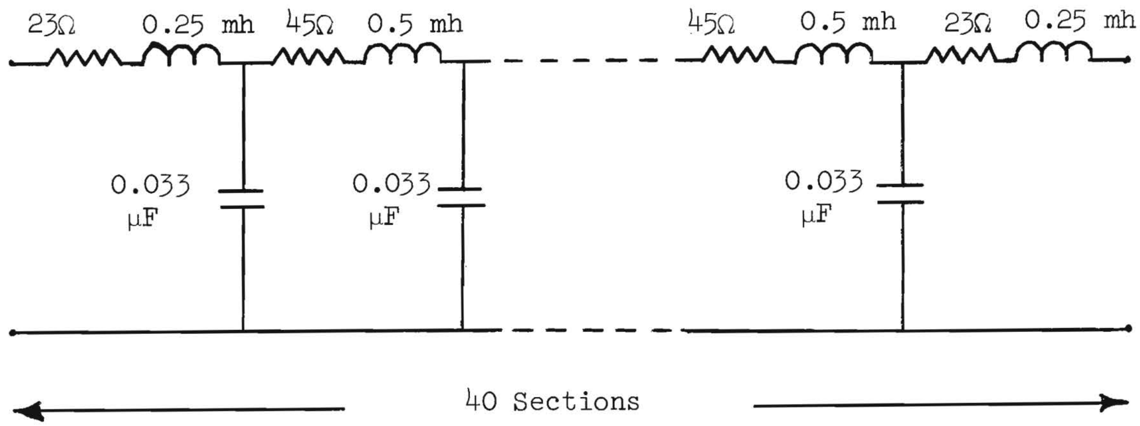
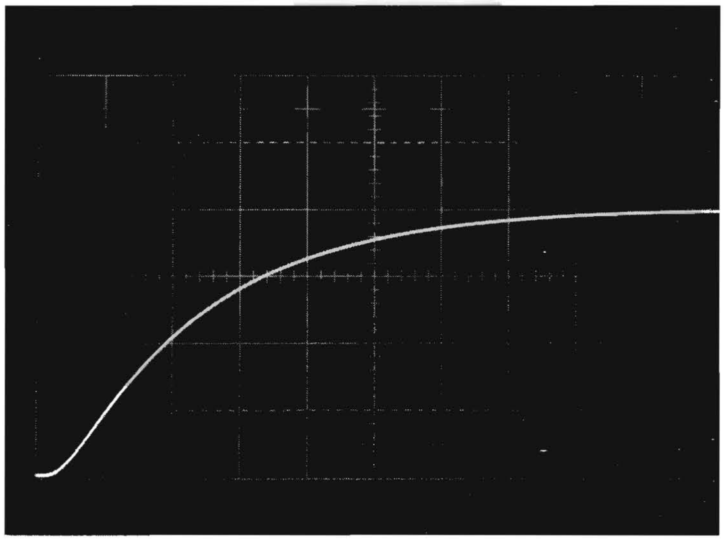


Figure 3. RLC analog of twisted-pair line.

This model includes all line parameters except leakage resistance. The leakage resistance of 19 guage twisted pair is so large (1 megohm/mile or greater) that its effect could be neglected in the tests that were conducted.

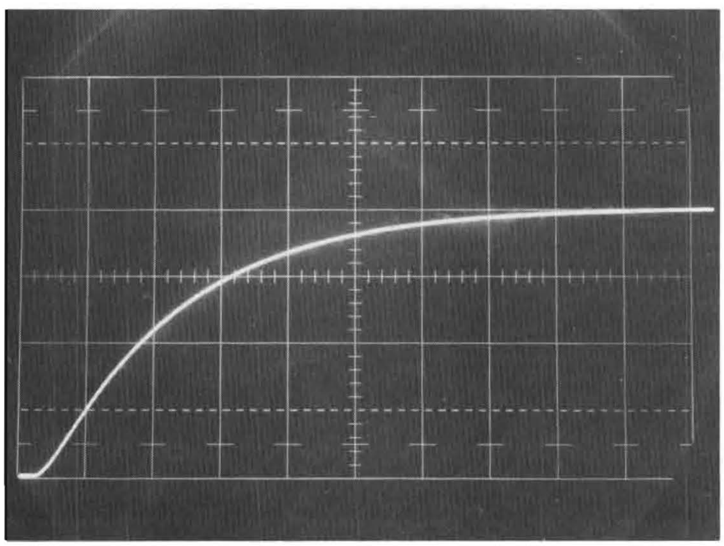
The time delay of each of the analog lines was measured by injecting an input voltage step into the line and measuring the output voltage response. These tests were made with the output end of the line open. The response of the RC line is shown in Figure 4 and that of the RLC line in Figure 5. These curves show the output voltage transient response of the two lines to be almost identical. They also show that the output voltage rises to approximately 90% of its final value in about 2.5 milliseconds.

In a further investigation of line response, the line was terminated with a Potter and Brumfield type KCP-11 relay (same type as



.5 ms/cm ⟶

Figure 4. Transient Response of 20 Mile Analog RC Line for Step Voltage Input. Trace Shows Open Circuit Output Voltage.



.5 ms/cm ⟶

Figure 5. Transient Response of 20 Mile Analog Line Including Inductance for Step Voltage Input. Trace Shows Open Circuit Outupt Voltage.

that used in the present KSC distribution system) and the output current response to an input voltage step measured. Two tests were run, one using the entire 20 mile line and the other using a 7 mile subsection of the line. The observed responses, shown in Figure 6, indicate that the rise of the current through the relay is much slower than the rise in output voltage on an open line. Further tests on the relay above (see Section II.C.) indicate that the curves in Figure 6 differ little from the current response of the relay alone. Thus, the time delay due to line effects is small compared to the delay in current response of the relay itself.

One mathematical technique for investigating the response of a transmission line is to calculate the phase delay as a function of frequency. The phase delay can be obtained from the imaginary part of the propagation constant of a general transmission line. The propagation constant is given by

$$p = \sqrt{(R + j\omega L)(G + j\omega C)} \quad , \tag{1}$$

where p is the propagation constant, ω is the frequency in radians/sec, and R, L, C, and G are the distributed line parameters. The phase delay may be obtained from the imaginary part of p

$$B = \text{Im}\,[p] \quad , \tag{2}$$

where B is the phase shift in radians per mile. Dividing the phase

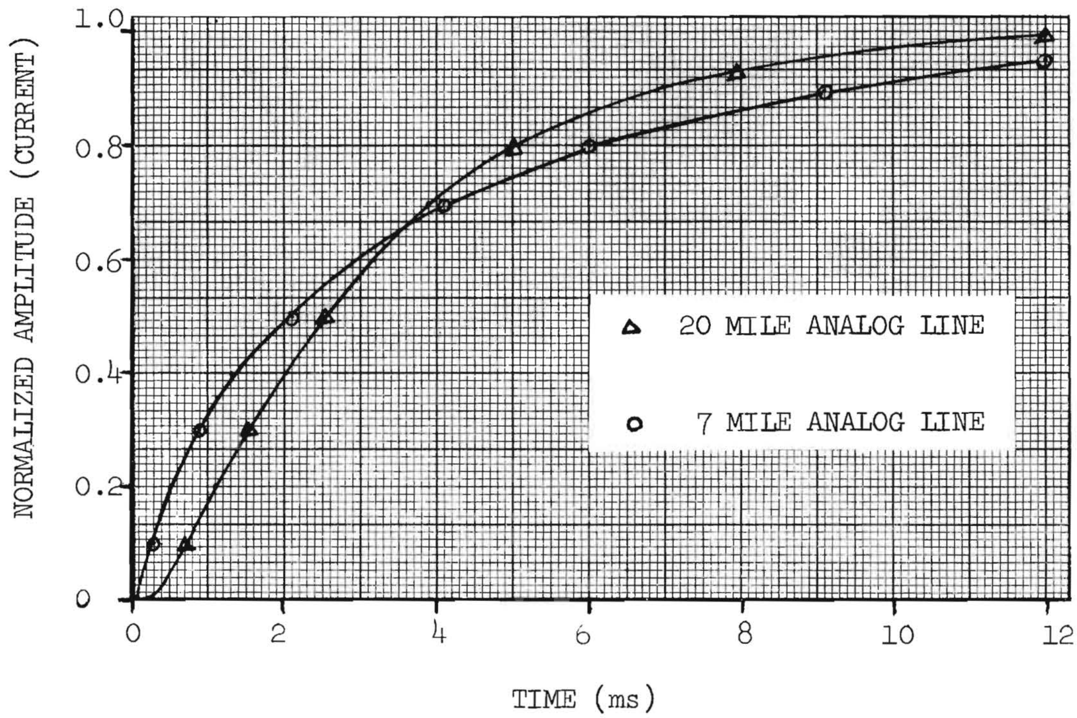


Figure 6. Current response at the output of terminated line due to input voltage step.

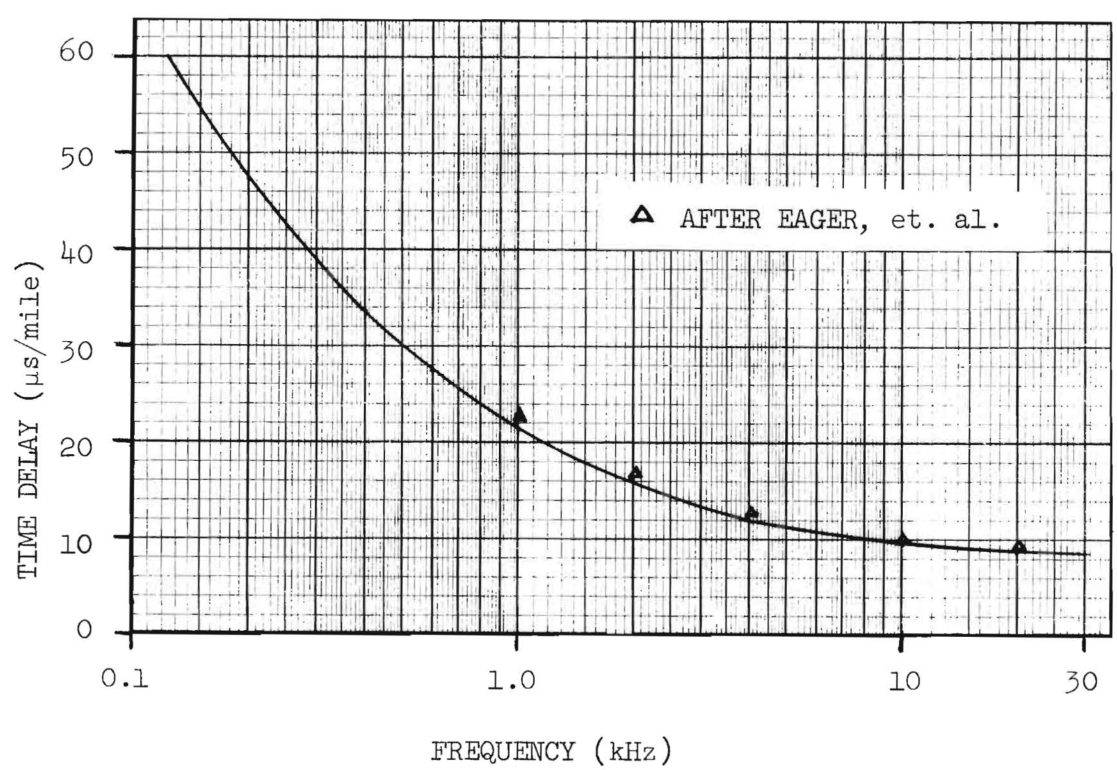


Figure 7. Time delay for various frequencies on 19 guage twisted-pair cable.

shift of Equation (2) by the radian frequency gives the time delay as a function of frequency,

$$t_d = \frac{B}{\omega} \quad , \tag{3}$$

where t_d is the line time delay in seconds per mile of transmission line. With the line parameters of the 19 guage twisted-pair line inserted, Equations (2) and (3) were evaluated for various frequencies. The results of these calculations, shown in Figure 7, verify the transient response curves of Figures 4 and 5 in that the longer delay of the lower frequencies gives rise to a slowly rising step response. Also shown in Figure 7 is the measured time delay as determined by other investigators.[1] Note that high frequencies undergo an almost constant delay of approximately 8 microseconds per mile. Close observation of the transient response curve of Figure 5 for the RLC analog line shows a minimum propagation delay of about 130 microseconds. This value agrees fairly well with the theoretical value of 160 microseconds (8 μs/mile x 20 miles).

To verify the general results of the analog line transient response measurements, the step response of an actual line was observed. Figure 8 shows the step response of a twisted-pair loop of length approximately 12.8 miles. The initial pedestal was due to cross-talk between the outgoing and return lines. The sharp rise at about 100 microseconds is the actual leading edge of the return pulse. The observed minimum propagation time of about 100 microseconds agrees

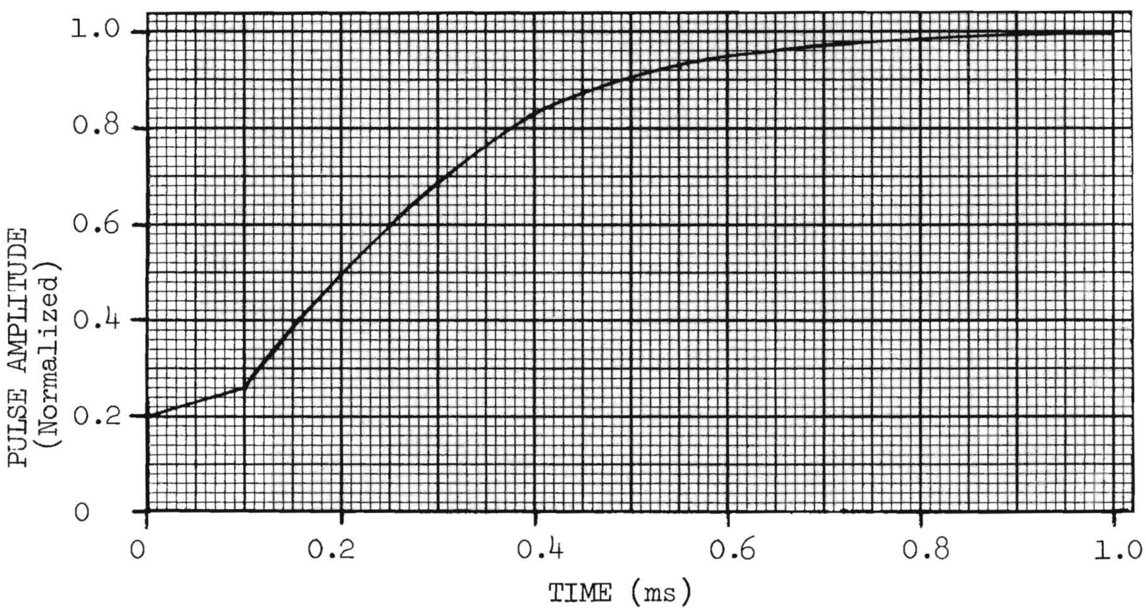


Figure 8. Voltage response at the end of 12.8 mile loop due to input voltage step.

quite well with the calculated value of 102 microseconds (8 μs/mile x 12.8 miles). Due to the shorter distance involved, the transient response of the actual line rises somewhat faster than the responses observed on the 20 mile analog lines; however, the general shapes of the response curves are in close agreement.

To further characterize the 19 guage twisted-pair line, loss versus frequency data were collected from the analog lines and from actual line measurements. Also, the theoretical loss as a function of frequency was calculated. An expression for the line loss as a function of frequency, can be obtained from the real part of Equation (1) as

$$L = K \operatorname{Re}[p] \quad , \tag{4}$$

where L is the line loss in dB per mile and K is a conversion factor for converting nepers to dB. Both the measured and calculated values were normalized to a line length of one mile for comparison, and the results are shown in Figure 9. The theoretical loss curve applies only to a line terminated in its characteristic impedance; measured loss curves are shown for both open lines and lines terminated in a 600 ohm resistive load. With the exception of the curve for the actual line with no load, all of the loss curves agree very closely for low frequencies. This agreement further supports the conclusion drawn from the transient response data taken from the two analog lines (Figures 4 and 5) that both lines characterize the low frequency response well. For frequencies above 4 or 5 kHz, the RC analog line does not accurately represent the actual line. The RLC analog line loss curve, however, approximates the actual line loss curve up to about 50 kHz. The theoretical loss curve also approximates the actual line loss curve up to about 50 kHz. Above 50 kHz, the theoretical loss curve approaches an asymptotic value of 3 dB per mile while the loss curve for the actual line continues to drop. This difference is probably due to the fact that the distributed line parameters are frequency dependent while the theoretical loss was calculated using fixed parameters which were obtained from low frequency data.

From measured line loss curves of the type shown in Figure 9, a "worst case" loss curve for 19 guage twisted-pair cable was extracted by taking an upper bound of all the loss data. Loss curves used in this determination were based on (1) measurements made on the RLC analog

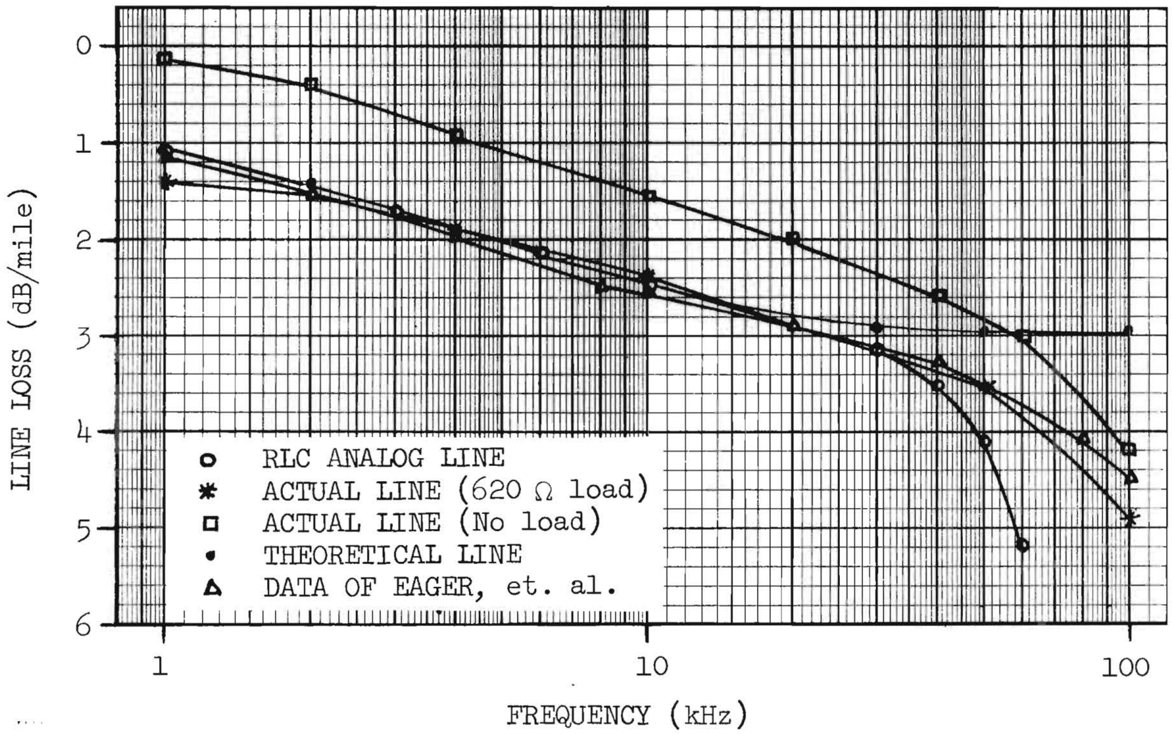


Figure 9. Loss vs frequency for 19 guage twisted-pair cable.

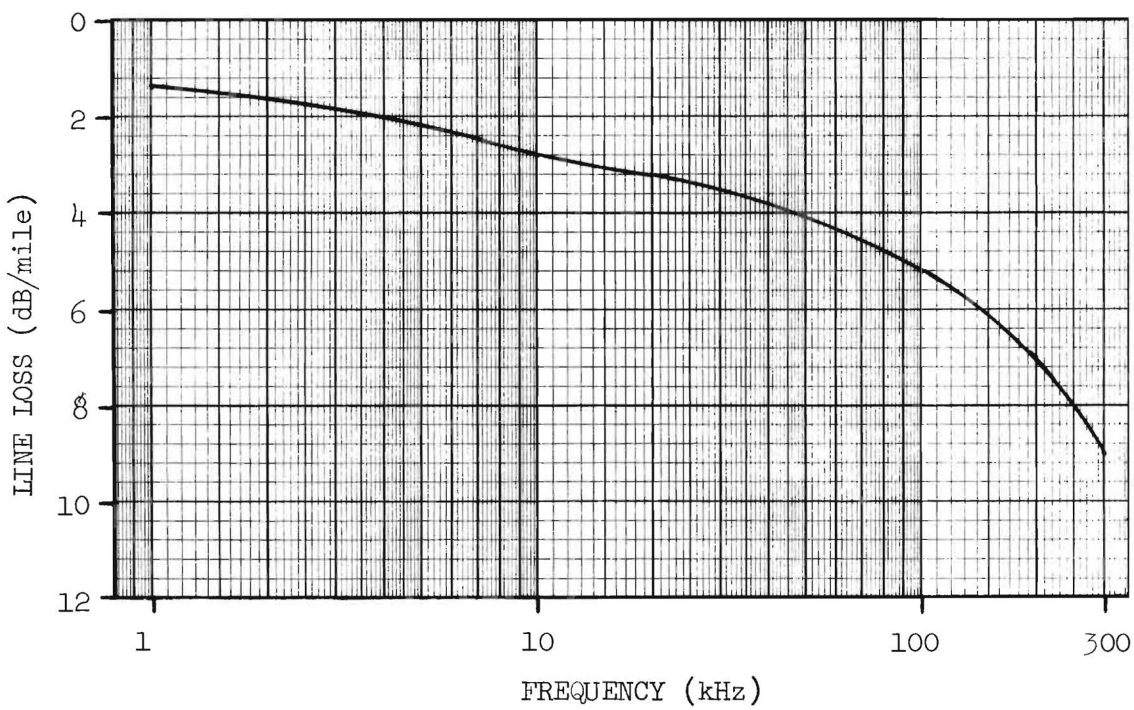


Figure 10. Conservative loss vs frequency curve used for estimating maximum losses.

line, (2) measurements made on actual lines at KSC, and (3) published data.[1] This worst case curve is shown in Figure 10, and values were taken from this curve to provide conservative estimates of line losses in all subsequent calculations relative to a system.

The curves shown in Figures 7 and 10 essentially summarize the characteristics of the 19 guage twisted-pair cable used in the present KSC distribution system. Estimates of time delay for various frequencies can be obtained from Figure 7 while conservative estimates of line losses can be obtained from Figure 10. The response to an input voltage step is not easily deduced from these two figures, however, since such a step contains all frequencies. It can be deduced that the initial rise of the pulse will not occur until sufficient time has elapsed for the highest frequencies to propagate down the line. This requires about 8 μsec/mile; thus for a 20 mile line about 160 μsec would elapse before the initial rise would occur. Further conjectures about the nature of the step response are better based on the measured response curves shown in Figures 5 and 8. Although the curve shown in Figure 5 was obtained from measurements on the RLC analog line, this model has been found to be a good representation of an actual line for frequencies below 50 kHz, and most of the power in a voltage step exists at frequencies well below 50 kHz.

Based on Figures 5 and 7, the response at the end of a 20 mile line to an input voltage step would begin in about 160 μsec and would require about 2.5 milliseconds to rise to 90% of its final value. This does not preclude delivering a signal in less than 2.5 milliseconds.

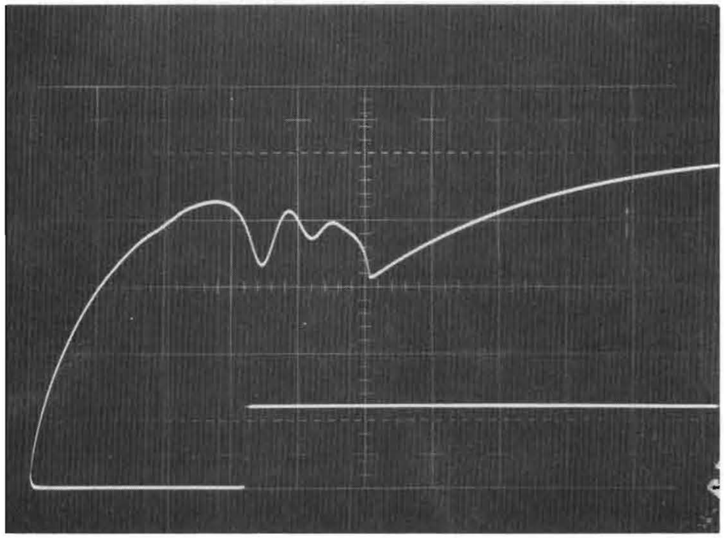
By using a fast acting electronic sensor and setting the triggering level well below the peak value, an indication could be obtained while the pulse is still rising. The lower limit to which the triggering level could be set would be restricted by system noise, but output indications in approximately 0.5 milliseconds appear practical.

C. Relay Characteristics

Since the studies of the transmission line failed to reveal any reason for the long time delays experienced in the present distribution system, a relay of the same type (Potter and Brumfield Type KCP-11) as that used in the system was obtained and tested. Measurements were made of the relay response time when driven directly and when driven through analog lines.

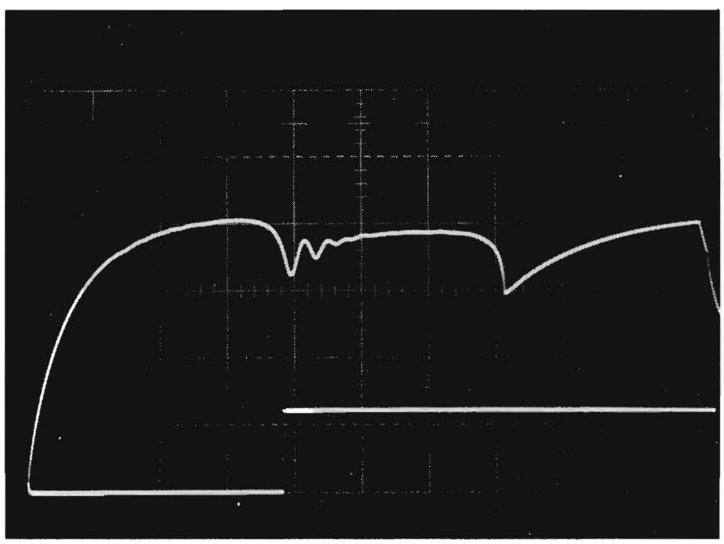
When the relay was driven directly with its normal operating voltage of 28 volts, the relay closure time was observed to be about 15-16 milliseconds. Figure 11 shows, in the upper trace, the current build-up in the coil when driven with 28 volts. The lower trace of this figure shows the voltage on a circuit completed through the relay contacts; the break in the curve designates contact closure.

Further experiements showed the relay response time to vary markedly with driving voltage. Figure 12 shows the current build-up and closure time for below normal operating voltage, and Figure 13 shows the same for above normal voltage. Note that the horizontal time scale on Figure 12 is different from that on the other two figures. A plot of the observed closure times vs operating voltage is shown in Figure 14. When the driving step was dropped to 21 volts, closure time



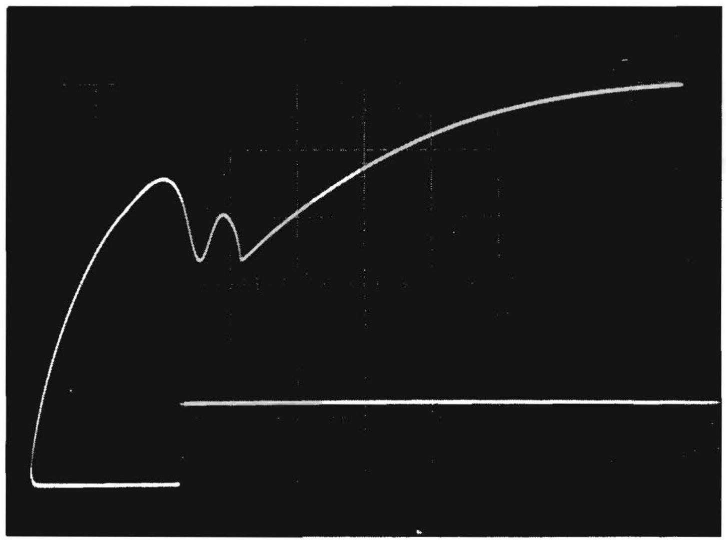
5 ms/cm ⟶

Figure 11. Direct Operation of KCP-11 Relay on 28 Volts. Lower Trace Shows Time Delay before Relay Closure.



10 ms/cm ⟶

Figure 12. Direct Operation of Relay on 23 Volts. Lower Trace Shows Time Delay before Relay Closure. Note that Reduced Voltage Increases Time Delay before Closure.



5 ms/cm ⟶

Figure 13. Direct Operation of Relay on 34 Volts. Lower Trace Shows Time Delay before Relay Closure. Note that Increased Voltage Decreases Time Delay.

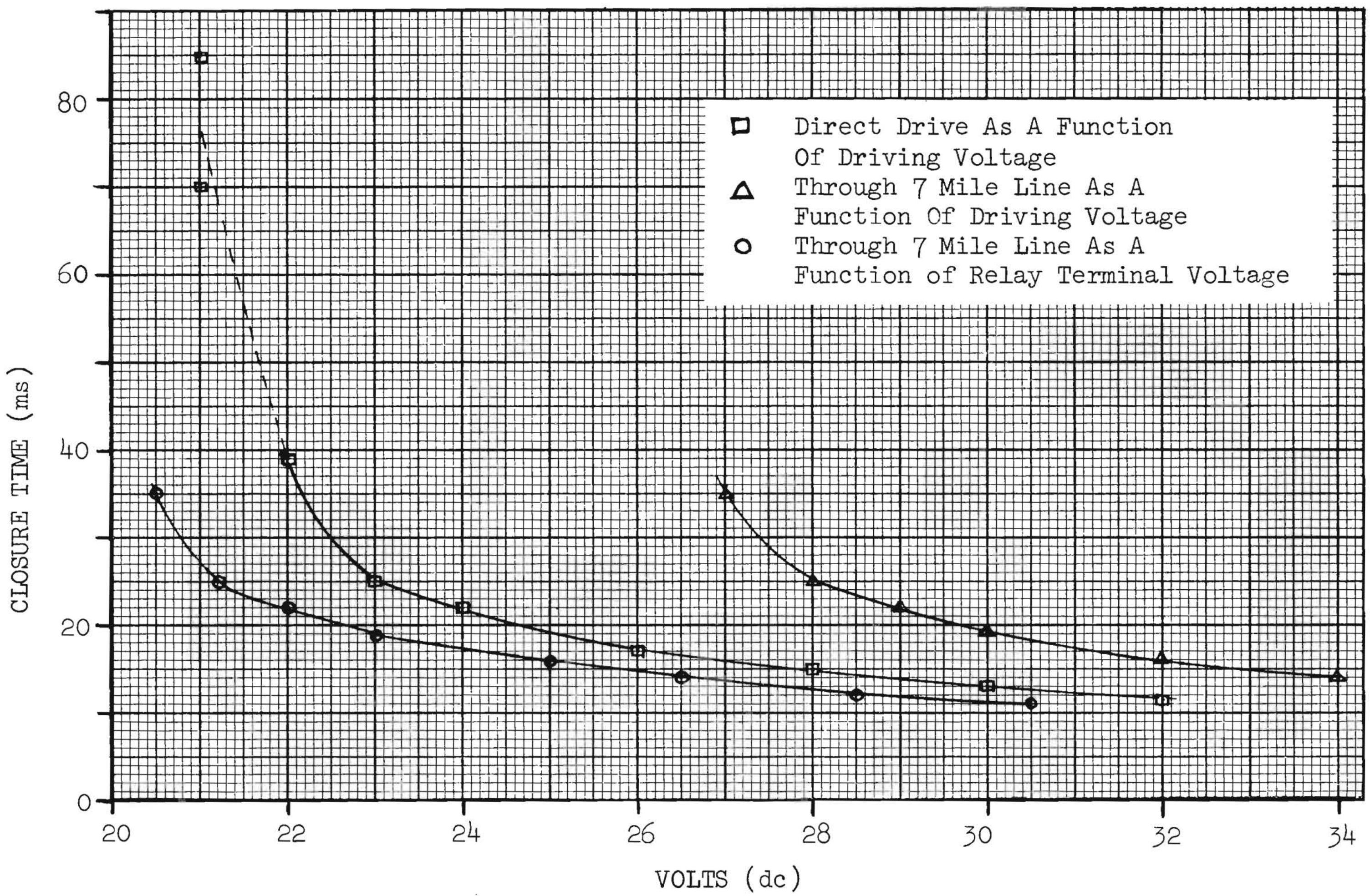


Figure 14. Relay closure time vs voltage.

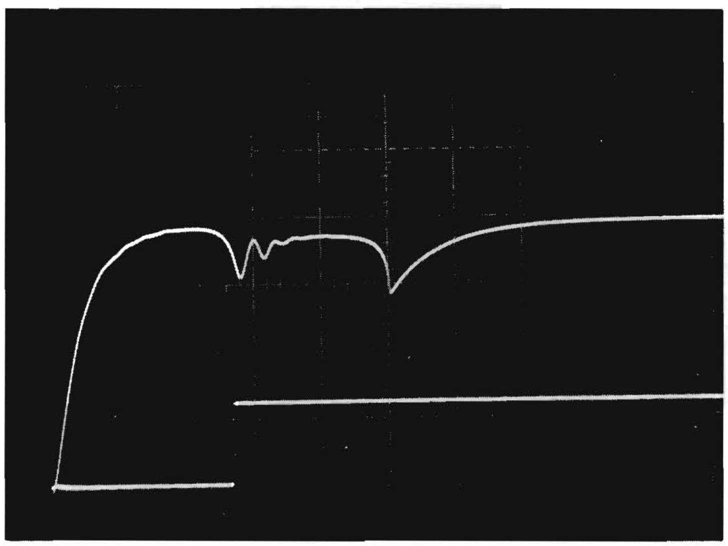
became erratic with times from 70 milliseconds to well over 100 milliseconds observed. At slightly less than 21 volts, operation ceased.

This relay was also driven through the RC analog line using line lengths of both 7 and 20 miles. In each case the DC resistance of the line is an appreciable part of total circuit resistance, hence, the steady state voltage at the relay terminals is well below the voltage impressed on the line. When the relay was driven through the 7 mile line with 28 volts impressed on the line, closure time was about 25 milliseconds. The steady-state voltage at the relay terminals was 21.2 volts. By varying the driving voltage, data were obtained on the relay closure time as a function of both the voltage input to the line and the steady-state voltage at the relay terminals. These data are also presented in Figure 14.

One oddity about Figure 14, the fact that the relay closes faster for a given terminal voltage when driven through the line than it does when driven directly, is easily explained. The time delay on current build-up in the relay coil is so much greater than the time delay on the line that the voltage at the relay terminals rises rapidly to a value near that of the driving voltage step. After peaking, the terminal voltage will drop due to IR loss on the line as the current rises. This temporary overshoot of the voltage at the terminals provides an extra driving impulse to the relay and effects faster closure. It also gives reliable operation at terminal voltages slightly below the minimum voltage that would operate the relay when driven directly.

These data show that in order to have 28 volts impressed on the relay terminals in the present KSC event distribution system, the driving voltage applied to the line should be increased to about 36 volts. If such an increase were made, relay closure time could be cut in half in the present system.

Experiments were also conducted in which the relay was driven through the 20 mile RC analog line. In these experiments, the increased IR drop on the line made it necessary to increase the driving voltage above 28 volts before the relay would operate. Figure 15 shows the current in the relay coil (upper trace) and contact closure time for the relay when driven with 40 volts input to the line. For this case, the voltage at the relay terminals after the transient subsided was about 24 volts.



10 ms/cm ⟶

Figure 15. Operation of KCP-11 Relay through 20 Mile Analog RC Line. 40 Volts into Line. Lower Trace Shows Time Delay before Relay Closure.

III. Event Distribution Using Twisted-Pair Lines

A. General

Since the studies of the characteristics of 19 guage twisted-pair lines discussed in Section II indicate that transmission over these lines can meet the time requirements of the event distribution system, the problem of designing an event distribution system around these lines was pursued. The use of twisted-pair lines for the event distribution system has several advantages. Generally, a wired system will be more reliable than a wireless system; it will also be easier to maintain. These advantages together with the fact that twisted-pair cables are already installed in the Saturn launch complex makes the use of these cables in a system very attractive.

Using twisted-pair cable for an event distribution system does not lead immediately to a single system design. The possible systems fall into two categories, (1) the use of one line to carry one event signal, and (2) the use of one line to carry several event signals.

The one event per line system would be the easiest and cheapest to implement. This system is described in Section III.B. The use of a single pair to carry multiple event signals requires consideration of a number of factors, and these are discussed in Section III.C.

B. One Event Per Line

The method of achieving a 1 millisecond system in which each event was signaled over a separate line was mentioned in Section II.B., namely replacing the mechanical relay in the present distribution system with an electronic sensing device.

One form of electronic detector which seems ideally suited to this problem is the Schmitt trigger. To test this type system, a laboratory model of the Schmitt trigger circuit shown in Figure 16 was constructed. Note that the trigger was provided with adjustments to set the triggering threshold.

This trigger was tested as an output indicator for signals transmitted over both the RC analog line and over an actual line at KSC. In each case the input signal was a DC voltage step.

When the trigger was operated on the 20 mile RC analog line, the trigger was actuated when the output voltage level (See Figure 4) rose to the threshold level. The response time of the trigger could be varied by adjusting the threshold. With a driving voltage step of 10 volts into the line, reliable operation was achieved with the threshold adjusted to give a response time of 150 μsec. In similar tests using a 7 mile subsection of the line, response times down to 30 μsec were obtained. Of course, these response times were obtained with the triggering threshold set very low. On actual lines the lower limit to which the threshold could be adjusted would be restricted by the noise on the line. The threshold must be above the peak noise encountered to prevent false indications. Note in Figure 4 that on a 20 mile line a threshold level of approximately 50% of the peak pulse amplitude could be used to give a response time of 1 millisecond. If the same 28 volt step used in the current system was used to drive the lines, the threshold could be set as high as 14 volts on a 20 mile path without exceeding the time requirement. Since noise levels on the lines should be limited to

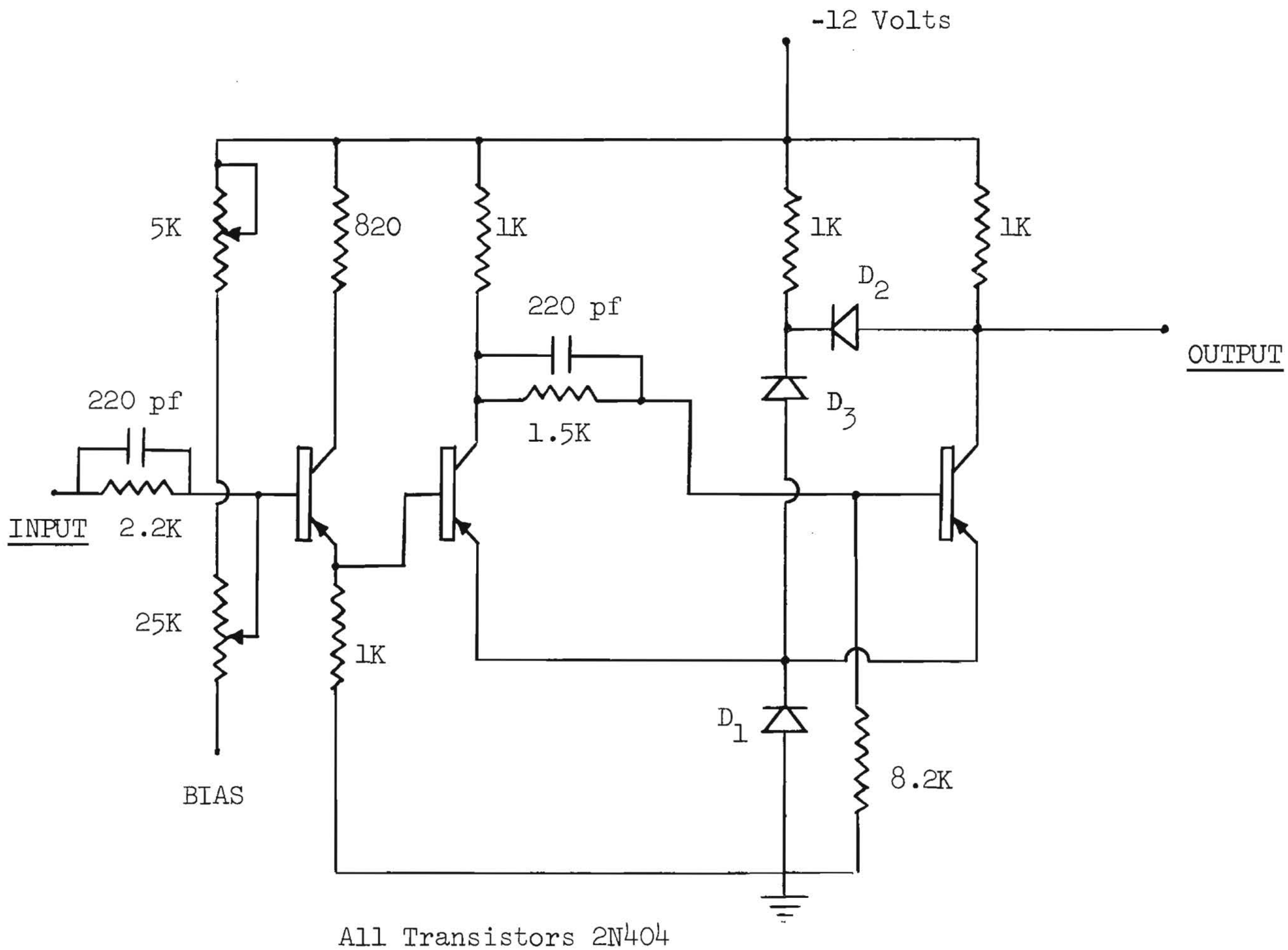


Figure 16. Low hysteresis Schmitt trigger circuit.

fractional volt levels, an ample margin exists for meeting the time requirement with minimal danger of false alarm.

This trigger was also tested on an actual line at KSC. The trigger was attached to the output end of the 12.8 mile loop for which Figure 8 shows the output pulse. With the triggering level adjusted to 50% of the peak output pulse amplitude, a response time of about 200 μsec was obtained. Noise on the line caused a jitter of about ± 10 μsec in the response time of the trigger. The fact that the jitter was that small shows that the noise on the line was small compared to the driving step. Unfortunately the input step voltage was not measured on this test, but it was much less than the 28 volts used as input in the present event distribution system.

Implementing a complete event distribution system using this technique would be attractive from the standpoint of system cost provided sufficient lines were available. The system would require one line to each receiving station for each event. Thus, for a 20 station, 30 event system, 600 lines would be needed. Since each line would be terminated with a Schmitt trigger, 600 triggers would be needed. However, such triggers can be constructed for a few dollars each. In quantities of hundreds, they could probably be obtained made to order for a price not exceeding $25 each.

In addition to the triggers, line driving buffer amplifiers might be needed. Since each event signal must be placed on 20 lines (one to each station), either the source of the driving voltage step must have a very low impedance or buffer amplifiers must be used between the voltage source and the lines. Suitable amplifiers would be relatively simple and could probably be obtained at a cost of about $25 each. Thus, even if 600 buffer amplifiers were required, the complete system could probably be implemented at a total component cost of about $30,000 or less exclusive of line costs.

C. Transmitting Multiple Events Over One Line

1. General System Concept

Since the use of one line to transmit each event requires a large number of lines, considerable effort was devoted to the possibility of using one line to carry several event signals. Basically, the general system concept for doing this is rather simple. Although 19 guage twisted-pair line has a nominal 3 dB bandwidth of about 3 kHz, frequencies well above 3 kHz can be transmitted over the line at somewhat higher losses. Considerably higher losses can be tolerated provided amplification is used on the output signal to restore it. If the cable affords sufficient bandwidth when used in this manner, then a number of signals can be multiplexed on the line.

The loss versus frequency characteristic of 19 guage twisted-pair line was discussed in Section II and is summarized in Figure 10. Preliminary consideration of these data indicated that frequencies up to perhaps 50 kHz or 100 kHz could probably be used on lines several miles in length. Following this determination, a small scale experimental program was undertaken to verify the feasibility of the method.

As a first step, it was necessary to decide on the method of multiplexing to be used. Considering the two most common methods of multiplexing, frequency division and time division, the choice lay clearly with frequency division multiplex (FDM). In time division multiplexing (TDM), the various signal channels are scanned in time sequence at the encoding (transmitting) end, and they must be decoded at the output end of the line by a similar sequencing device. For the event distribution system, several drawbacks to the use of TDM are readily apparent. First of all, the composite signal occupies a wide frequency band and must be transmitted with little distortion. To do this on twisted-pair line would require extensive equilization of the line. Also, the multiplexing and demultiplexing equipment for TDM systems is complicated, expensive and requires accurate synchronization between the two units. Finally, since the signal channels are sequentially scanned, a variable delay of up to one scan cycle would be involved in signaling each event.

The FDM system, on the other hand, seems ideally suited to the requirements of the event distribution system. In the FDM system the frequency domain rather than the time domain is divided, and each signal has its own frequency band (channel). In the usual FDM system, which is used to carry audio information, an oscillator is used to generate a sub-carrier in the channel and the audio signal is used to modulate the sub-carrier oscillator.

The requirements of the event distribution system permits an even simpler system. Since the event signals are binary in character, no modulation of the sub-carrier is required. Instead, the sub-carrier can simply be normally off and be gated on when the event occurs.

Since the signal is simply a sine wave, very little channel bandwidth would be required for its transmission in the steady state. However, the channel bandwidth will definitely affect the rise time of the signal. It was estimated that a channel bandwidth of about 4 kHz would be sufficient to meet the time requirements of the event distribution system.

2. Feasibility Test

An experiment was conducted to test the general system concept and to verify the adequacy of a 4 kHz channel. Only a single channel was tested and a center frequency of 30 kHz was selected for the test. A 4 kHz bandpass filter centered at 30 kHz was constructed. An oscillator was used to generate a 30 kHz frequency which was passed through the filter to the line. In a test conducted on a 6.4 mile line at KSC, the range timing pulse was used to trigger the oscillator at one end of the line and a scope at the other end. With the oscillator output adjusted to give a 1 volt peak-to-peak signal into the line, the envelope of the output waveform shown in Figure 17 was obtained. Note that the output signal reaches 50% of its final value in about 325 μsec. This is the total time delay caused by both the line and the filter, but most of the delay is attributed to the filter.

This test, though quite limited in scope, demonstrates the feasibility of the method. With a trigger circuit adjusted to fire

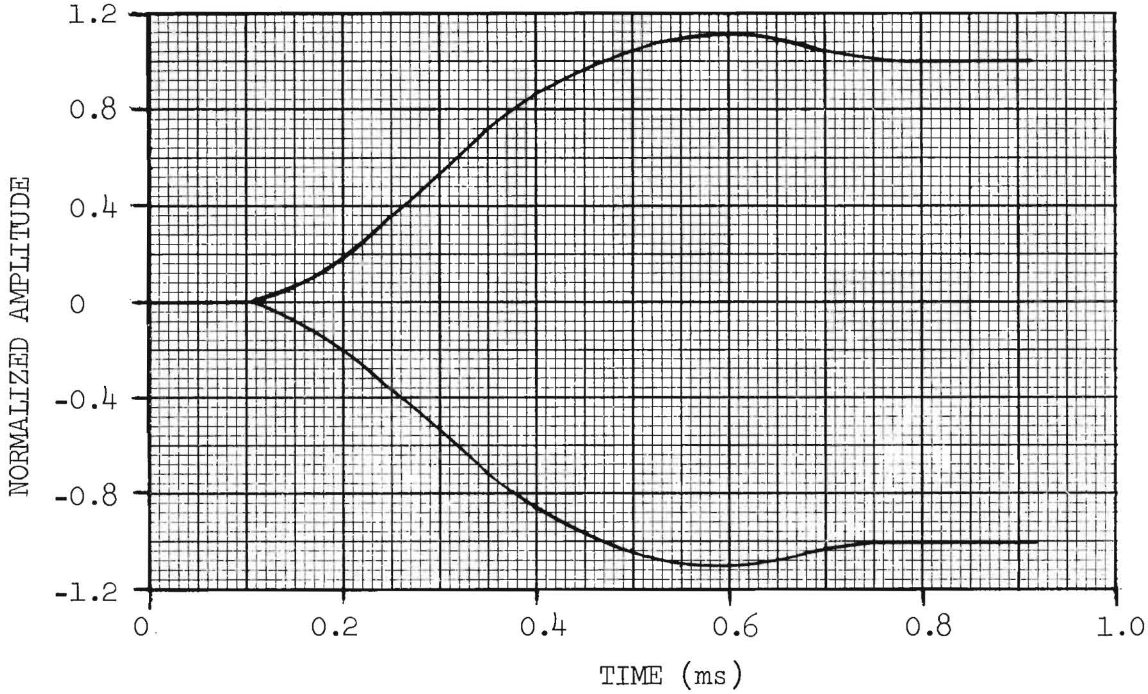


Figure 17. Envelope of pulsed 30 kHz burst as received over 6.4 mile twisted-pair line.

at 50% of the peak signal level, an indication would have been available at the end of the 6.4 mile line in 325 μsec.

3. System Planning

Following the feasibility tests, attention was directed toward laying out a system design. Some difficulty was encountered in carrying out this effort on a strictly theoretical level. Lack of precise data and exact criteria in many areas required that engineering estimates of various parameters be made. In spite of these difficulties, the problem was pursued and a fairly detailed design evolved. It should be kept in mind, however, that the design is tentative and should be subjected to testing before an attempt is made to adopt it as an operational system.

As a first step in discussing the design, the overall objectives and the approach should be stated. Two main objectives were established. First, the system was to be capable of distributing events over a distance of 20 miles or less in not more than 1 ms; second, the event transmitting and receiving equipment was to be as simple as possible consistent with the efficient use of the information capacity of twisted-pair lines.

The line-linked system design problem was approached with the assumption that as many as 30 asynchronous events were to be distributed to 20 dispersed locations. These figures are conservative and could provide for expansion of the presently anticipated need of the KSC distribution facility. Since the events to be distributed are binary in character, no consideration was given to the preservation of analog signals. The characteristics of the twisted-pair line as a binary communications channel were then considered and subsystem requirements were established.

The following sections outline the essential design features of the twisted-pair line distribution system. It should be clearly emphasized that this system does not necessarily represent an optimum design. In several instances where detailed data were unavailable, conservative estimates of line electrical characteristics were used. Additional effort would be required to solve the interface problems likely to be encountered in this system. Such factors as the probability of receiving a false event signal would require a detailed analysis of signal conditions in the line environment.

4. Twisted-Pair Communications Channel

The time and frequency response characteristics of 19 guage twisted-pair, discussed in Section II, are summarized in Figures 7 and 10. In order to evaluate the effectiveness of the twisted-pair line as a communications channel, the line noise characteristics must also be considered. Since a given line may be in proximity to other signal-carrying lines, cross-talk levels as well as thermal and incidental noise affect the signalling capability of the line. For design purposes, all undesired signals were considered as noise sources. Although cross-talk noise depends on several factors such as frequency, pair proximity, and line length, a design estimate is that 70 dB of isolation between pairs can be achieved by using a balanced line drive.[1]

Since the input signal level to any line is limited to +7 dbm (KSC regulation), then the maximum noise level due to cross-talk that would be expected is -63 dbm. Theoretical estimates[3,4] of the thermal noise level indicate that it should be well below the level of noise due to cross-talk, hence, the maximum noise level is assumed to be -63 dbm.

For design purposes, a required peak signal-to-noise ratio of at least 20 dB was assumed. This high signal-to-noise ratio should provide some leeway for obtaining an output indication during rise of the step sinusoidal signal rather than waiting for the peak. The estimated noise level of -63 dbm and the assumed signal-to-noise ratio of 20 dB fix the minimum usable signal level at -43 dbm. The power relationships are summarized in Figure 18.

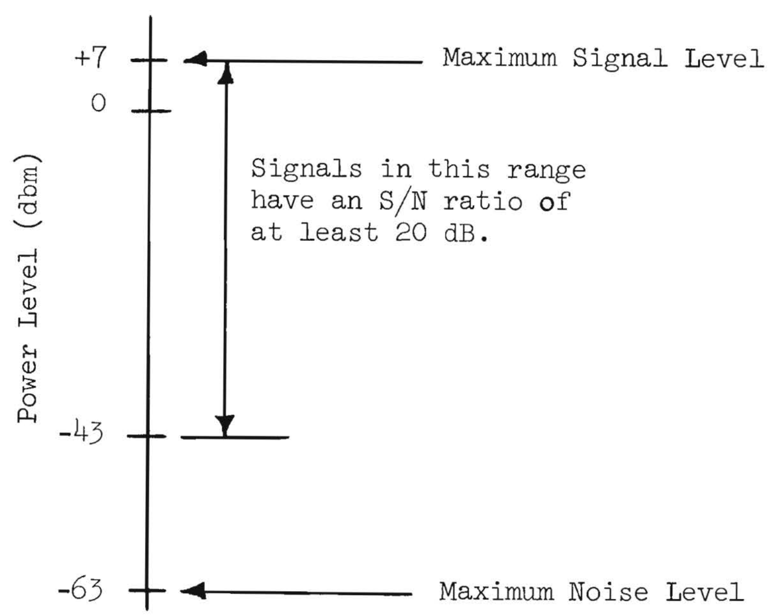


Figure 18. Power Level Diagram for a Twisted-Pair Line.

From the time and frequency response curves presented in Figures 7 and 10 and the power level diagram of Figure 18, the event distribution system using twisted-pair lines was designed. It is important to recognize that the design was based on these three essential line characteristics as presented in these figures.

5. Event Channel Multiplexing

As previously discussed, event signals will be combined for transmission on a single line by using frequency division multiplex. Also, each event will be signalled by gating on a sub-carrier oscillator, hence, the signal itself will be a step sinusoid.

The FDM signal on a single twisted-pair line would therefore consist of a number of different signal frequencies whose levels are step modulated in accordance with event step voltages. Since a step sinusoid has frequency components extending over a wide range, each event signal must be passed through a bandpass filter to prevent detrimental interference from adjacent event signals. Note from Figure 7 that event signals above 5 kHz may be transmitted over a 20 mile line in 250 μsec or less; therefore, in order to maintain a time delay of less than 1 ms, it is necessary that the FDM transmitting and receiving equipment have no more than 750 μsec time delay. Since threshold devices may be used to detect the event binary signals, it is not necessary that the received signal rise to its final value in minimum time; it is necessary only that the received signal rise to the detection threshold within the allotted time. For design purposes, a detection threshold at 50 percent of the final signal level was assumed.

A further study of bandpass filter transient response characteristics indicated that a filter having 4 kHz bandwidth and appropriate shape factor would allow the envelope of a step sinusoid to rise to a 50 percent level within 350 μsec.[5,6,7] Filter characteristics will be discussed in detail in a later section. The total time delay of an event signal passed through the bandpass filter and a 20 mile line would be approximately 600 μsec. To remain within the limit of 1 ms delay, the event receiving equipment must produce an event output signal within 400 μsec. If similar bandpass filters are used for transmitting and receiving, the total time delay would be approximately 950 μsec. Filter bandwidths larger than 4 kHz would reduce the net time delay; however, the number of event channels on a single twisted-pair line would be reduced correspondingly.

Depending on the design parameters to be optimized, event channel center frequencies may be selected in various ways. For example, if the design objective were to minimize net time delay, the center frequencies would be widely separated and the channel filters would be increased in bandwidth. In keeping with the design objective that the line capacity be fully utilized, the tabulation shown in Table I was used as an approximation to the optimum spacing of event channels that may be distributed over a single twisted pair. The maximum number of these channels that may be used on a given twisted pair depends on the line length. Note from Table I that the tabulation allows the use of 4 kHz bandwidth filters and 4 kHz guardbands. As indicated above, the worst time delay for event signals spaced in this fashion would be approximately

950 μsec. Obviously, line lengths of less than 20 miles would have less time delay.

With the event channel center frequency tabulation of Table I and the upper bound line loss curve of Figure 10, the attenuation as a function of distance may be determined for each channel. Figure 19 shows this relationship for channels 1-10, 15, 20, and 30. Note that the attenuation for higher frequency channels increases rapidly with distance. Since present restrictions in the KSC distribution complex limit the maximum power on a single twisted-pair line to +7 dbm (5 mw), it is necessary that the total power contributed to all channels not exceed this value. With such a total power restriction, the number of event channels on a single line would require that the power in each event channel be proportioned according to the line length and the channel loss characteristic. Using the minimum usable signal level of -43 dbm and the channel loss curves of Figure 19, the required input power for each channel may be determined as a function of line length. Figure 20 shows the relationship between line length, channel number, and required input power.

For a given line length, Figure 20 may be used to estimate the number of event channels that may be placed on a single twisted-pair line. The constraint that the total power level not exceed 5 mw may be expressed as

$$\sum_{i=1}^{N} p_i(L) \leq 5 \text{ mw} \quad , \qquad (5)$$

TABLE I

EVENT CHANNEL FREQUENCIES

CHANNEL NUMBER	CHANNEL CENTER FREQUENCY (kHz)
1	7
2	15
3	23
4	31
5	39
.	.
.	.
.	.
N	7 + (N-1)8

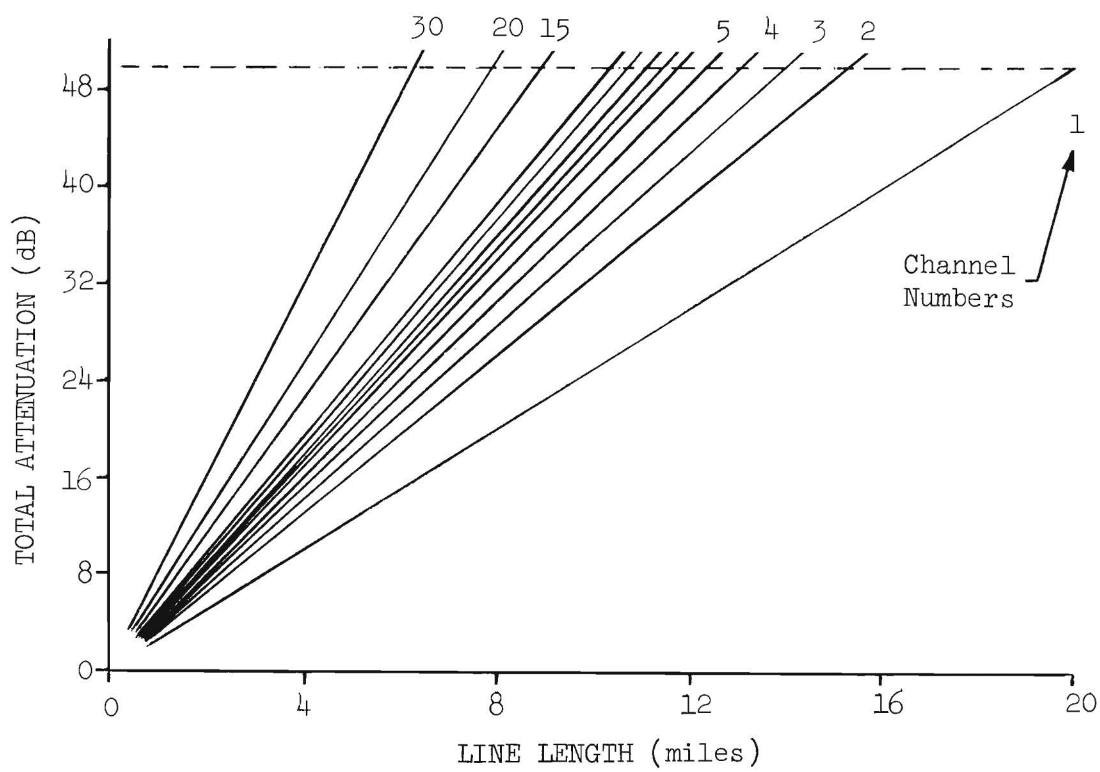


Figure 19. Total attenuation as a function of line length and channel number.

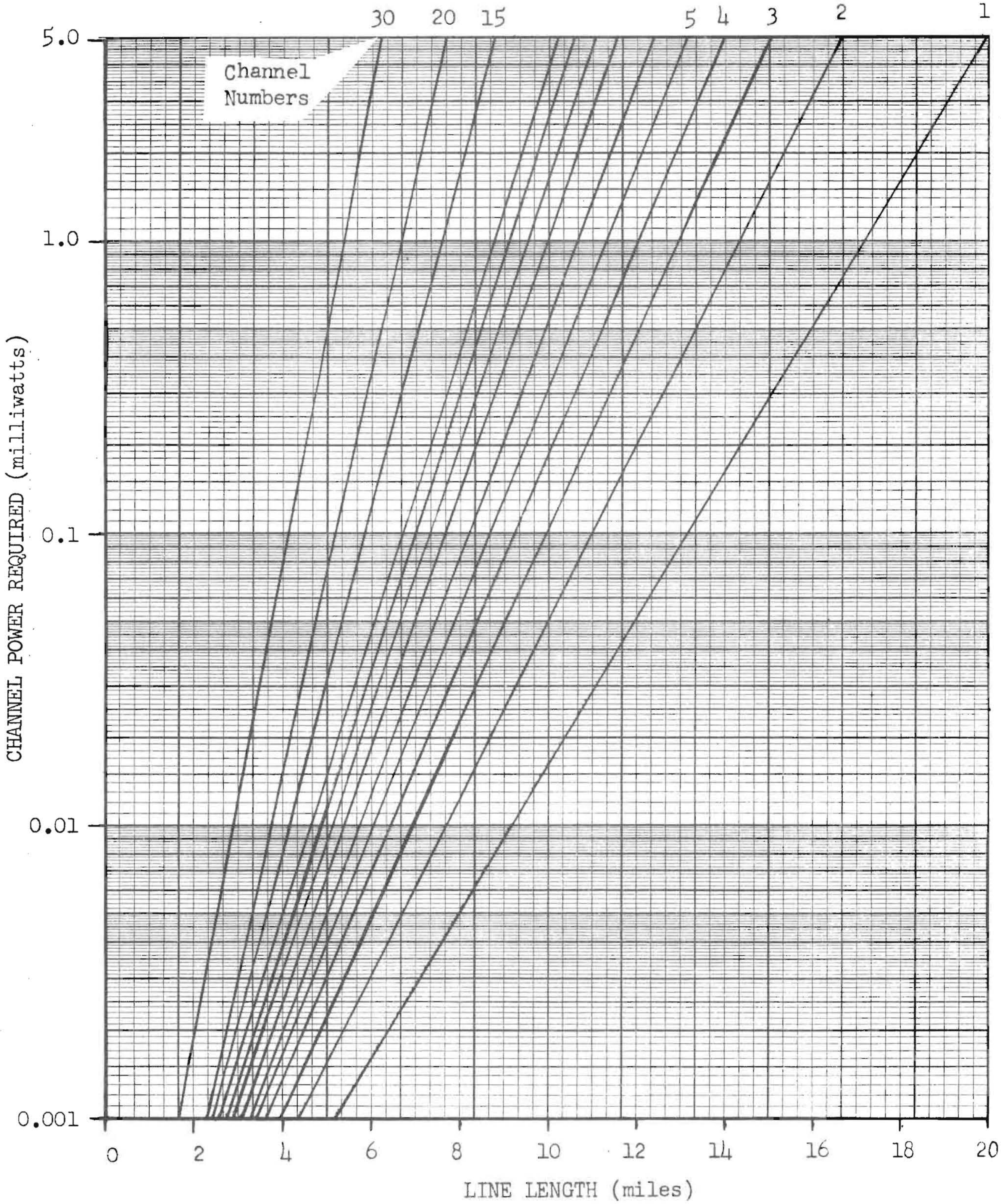


Figure 20. Input signal power required for 20 dB S/N ratio at line output.

where N is the number of channels per line, i is the channel number, and P_i is the required channel power for a line of length L. The maximum N that satisfies the above inequality is the maximum number of channels per line. For example, Figure 20 indicates that a 16 mile line will carry only channels 1 and 2. Figure 21 shows the estimated number of event channels per twisted pair as a function of line length. Note that as many as 20 channels may be multiplexed on a single line if the line length is 6 miles or less. With the aid of Figure 21 and the fact that the number of events is always an integer, the number of twisted-pair cables required to distribute 30 events over a fixed distance may be determined. Figure 22 shows this relationship. Note that the number of twisted pairs required increases rapidly for distances in excess of about 13 miles.

6. Event Transmitter and Receiver Design

As indicated above, each event signal in the FDM distribution system is a step sinusoid in the appropriate channel. To complete the basic design of the FDM distribution system, it was necessary to design event transmitters for generating these step sinusoids and event receivers for detecting the received signals. These two subsystem components are briefly described below.

An event transmitter suitable for generating one event signal is shown in Figure 23. Basically this device uses the event input signal to gate on a subcarrier oscillator signal. To limit its bandwidth, the gated sinusoid is then passed through a bandpass filter. A buffer amplifier is used to proportion the event signal to an appropriate

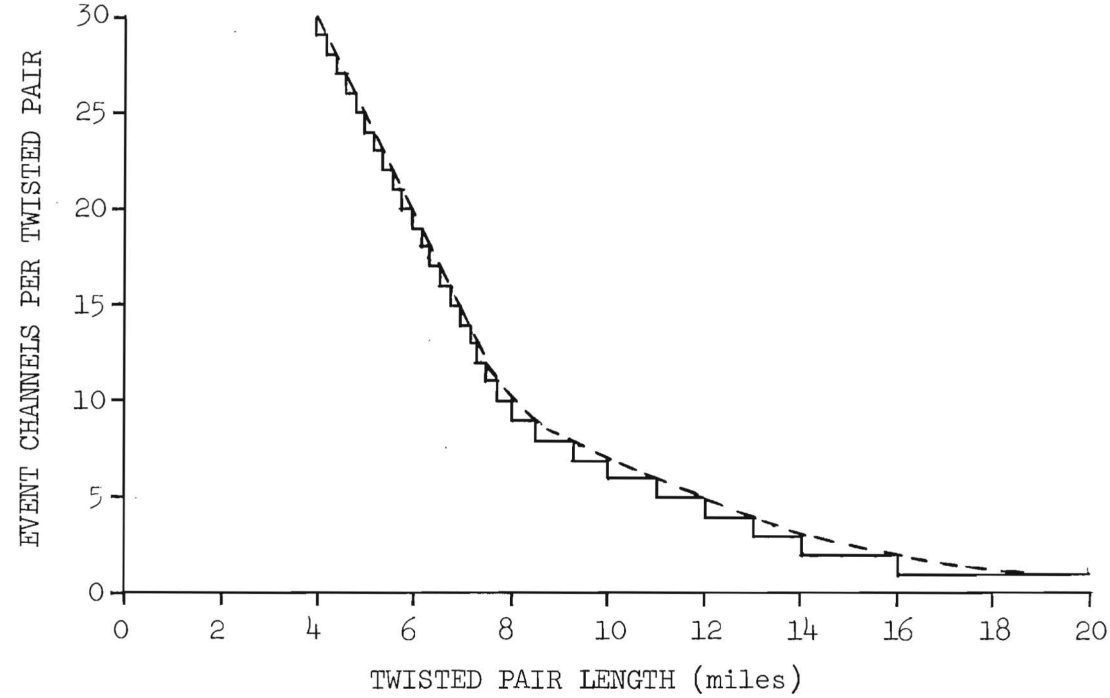


Figure 21. Channel capacity of line as a function of length.

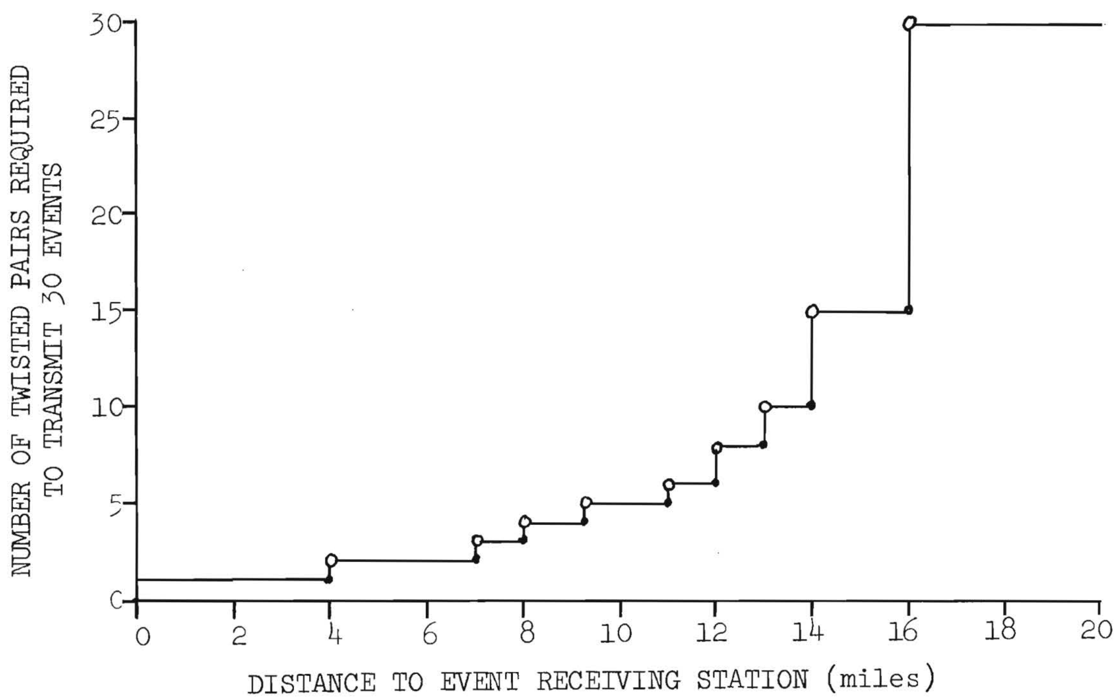


Figure 22. Number of pairs required to transmit 30 events as a function of path length.

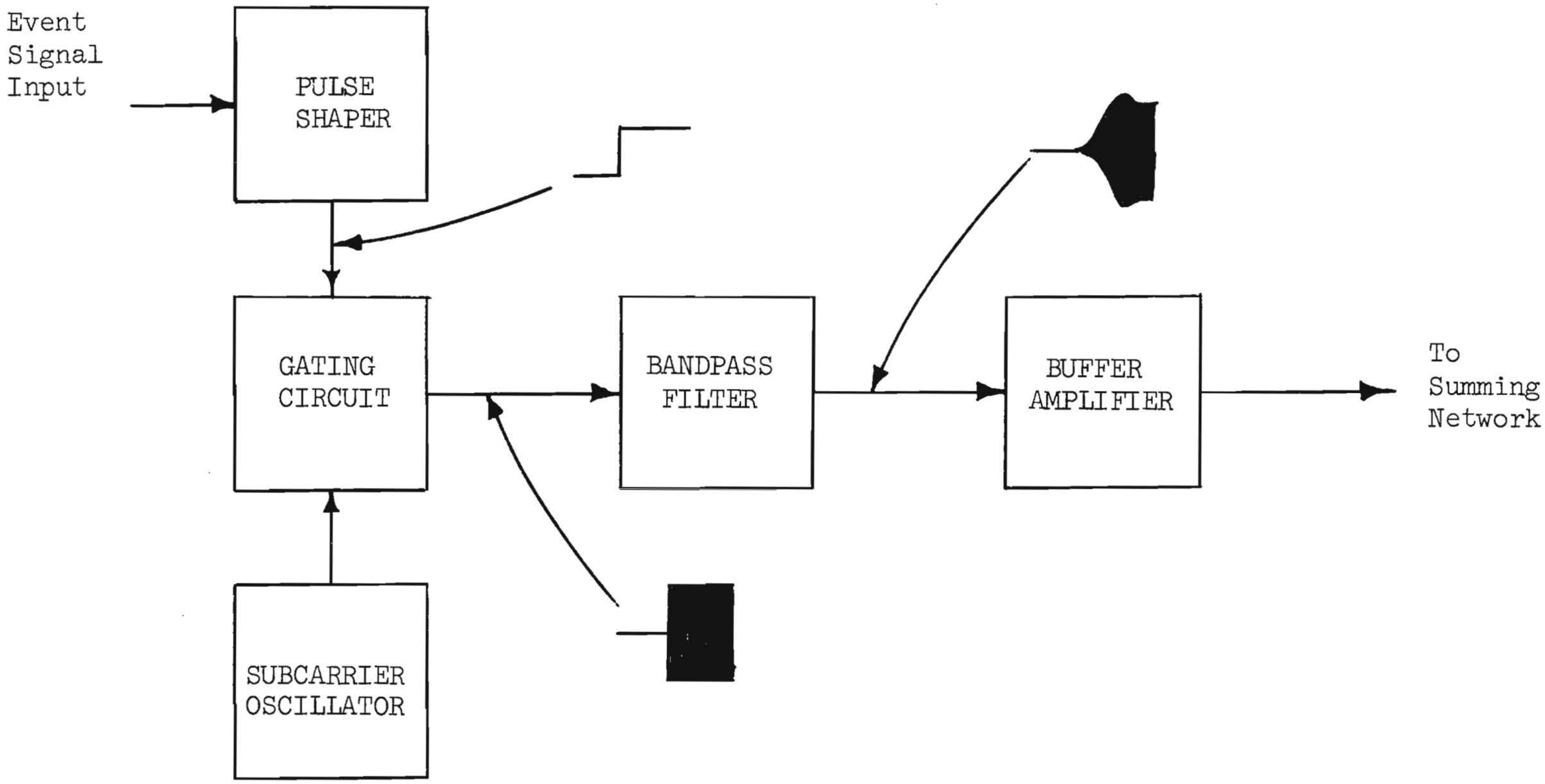


Figure 23. Event transmitter.

transmission level. A complete multi-channel event transmission system would utilize one event transmitter for each event to be transmitted. Such a transmission system is illustrated in Figure 24. Note that the outputs of the individual event transmitters are combined into one signal suitable for transmission over a single twisted pair. The exact number of event transmitters in Figure 24 depends, of course, on the channel capacity of the line to be driven. The combined outputs of the event transmitters are then amplified with a line driver amplifier. To reduce line-to-line cross-talk, the line driver amplifier has a balanced output.

The single most important element in the event transmitter of Figure 23 is probably the channel bandpass filter. Since this bandpass filter is the primary source of time delay in the transmission, its characteristics are of prime concern. Although a number of bandpass filters are used in the system, all bandpass characteristics are identical. The specifications shown in Figures 25 and 26 indicate requirements that might be imposed on the bandpass filters in a realistic system.

In order to detect a transmitted event signal, an event receiver such as the one shown in Figure 27 is necessary. This receiver is based on a superheterodyne concept in that the received event signal is heterodyned to a standard intermediate frequency, amplified, and then detected. Note that the receiver input is balanced to reduce cross-talk noise. A simpler receiver, such as an amplifier-filter combination, could possibly be used but would not be as versatile. The

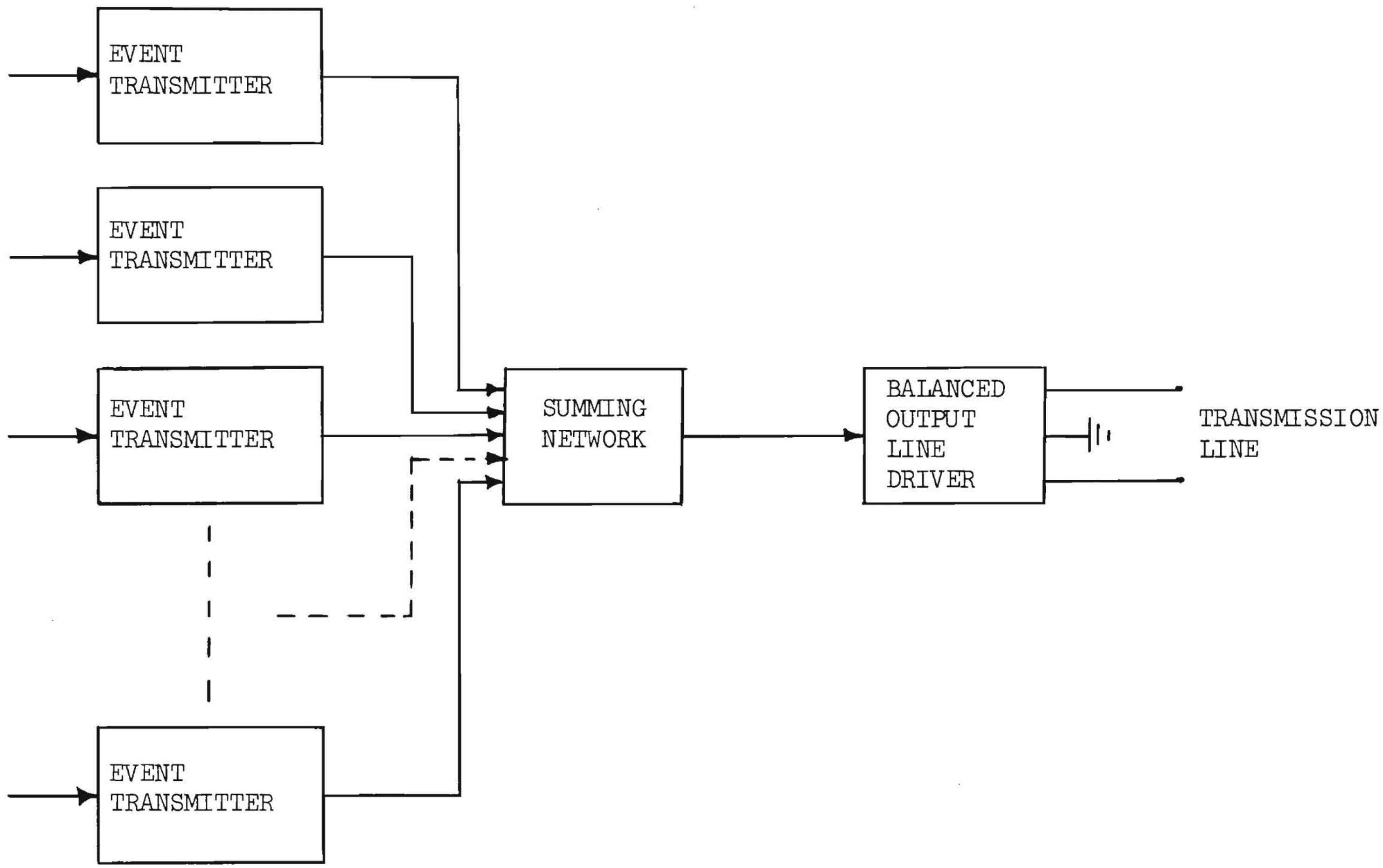


Figure 24. Event transmission system.

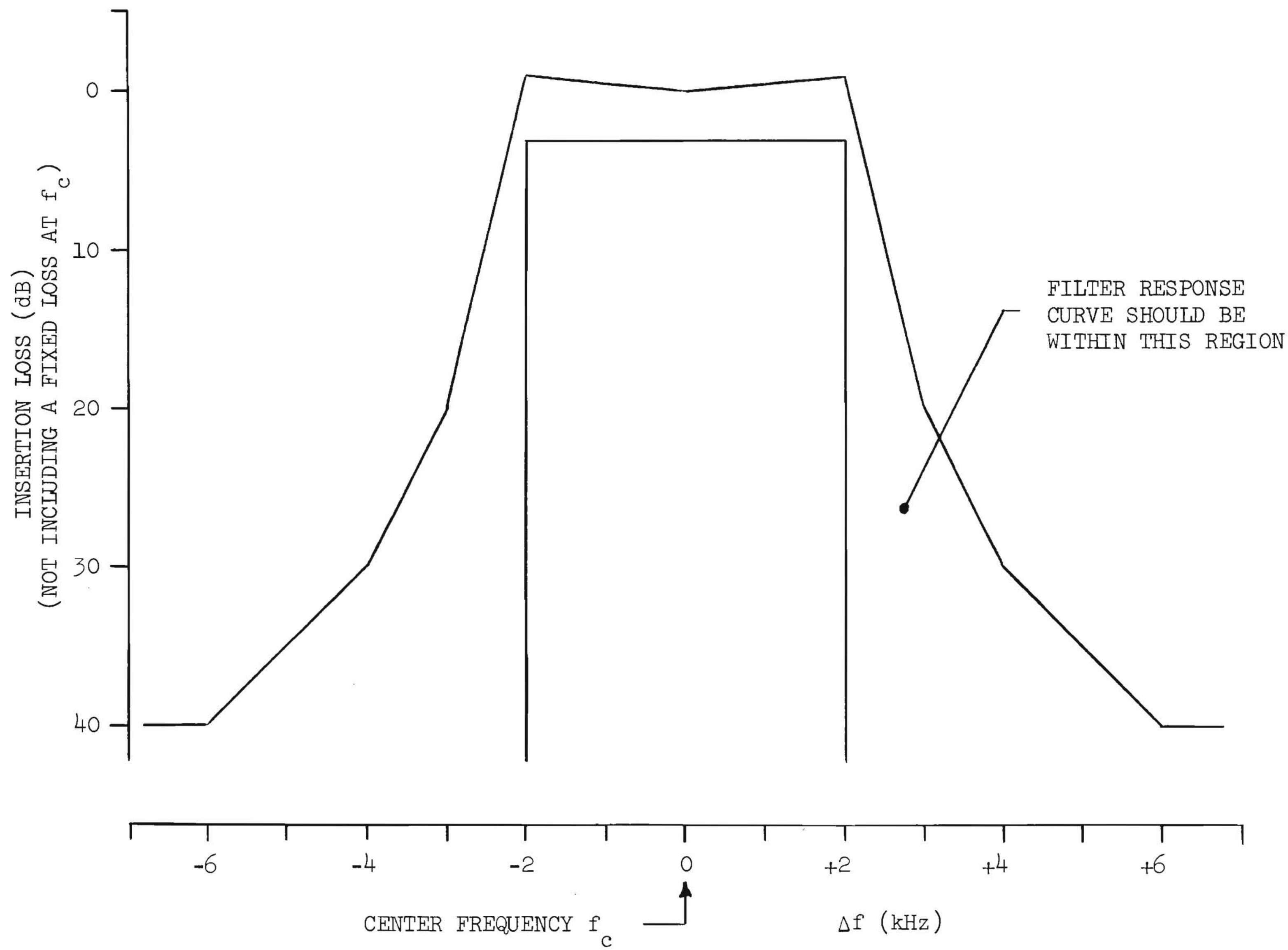


Figure 25. Filter bandpass characteristics.

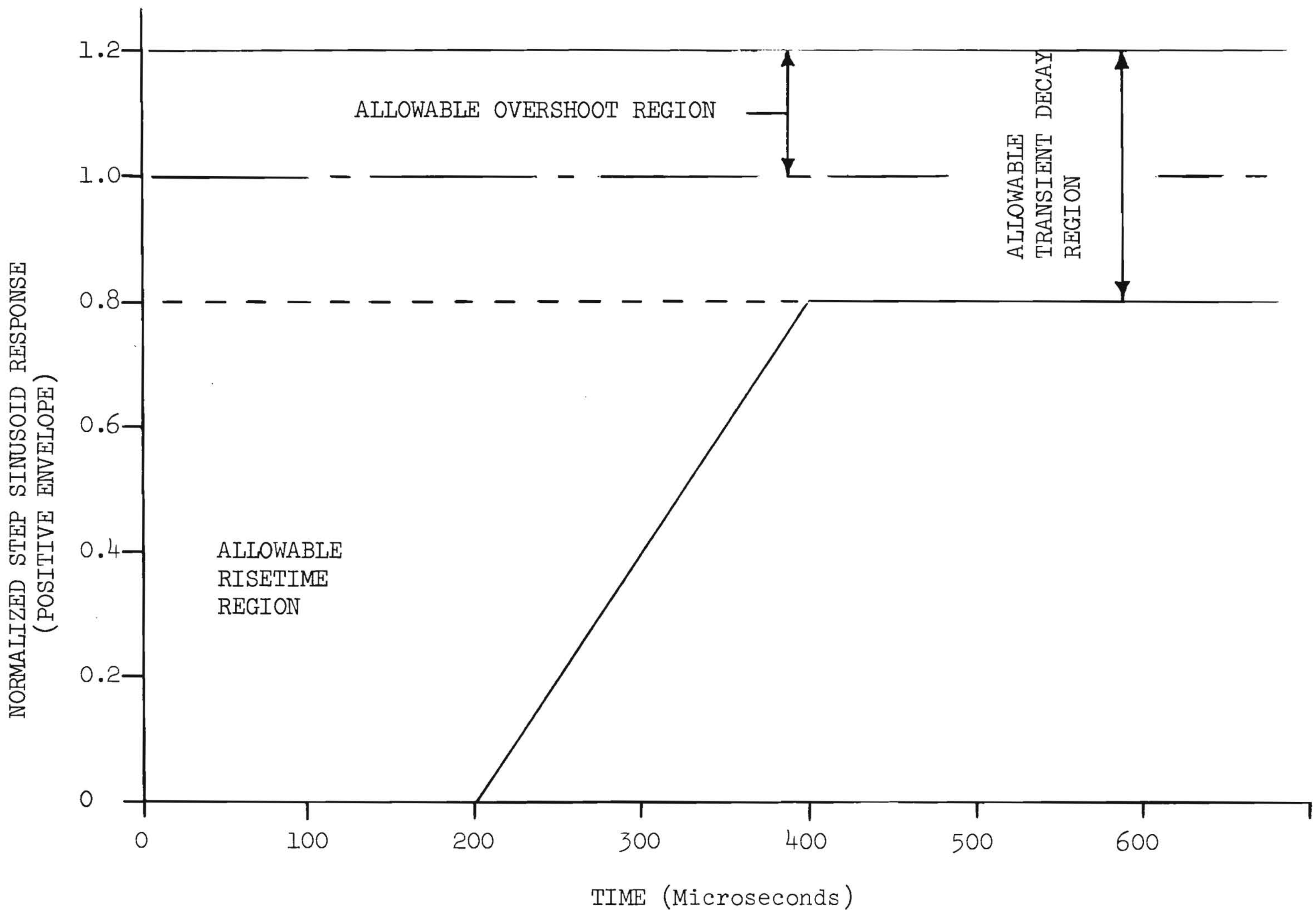


Figure 26. Filter transient response requirements.

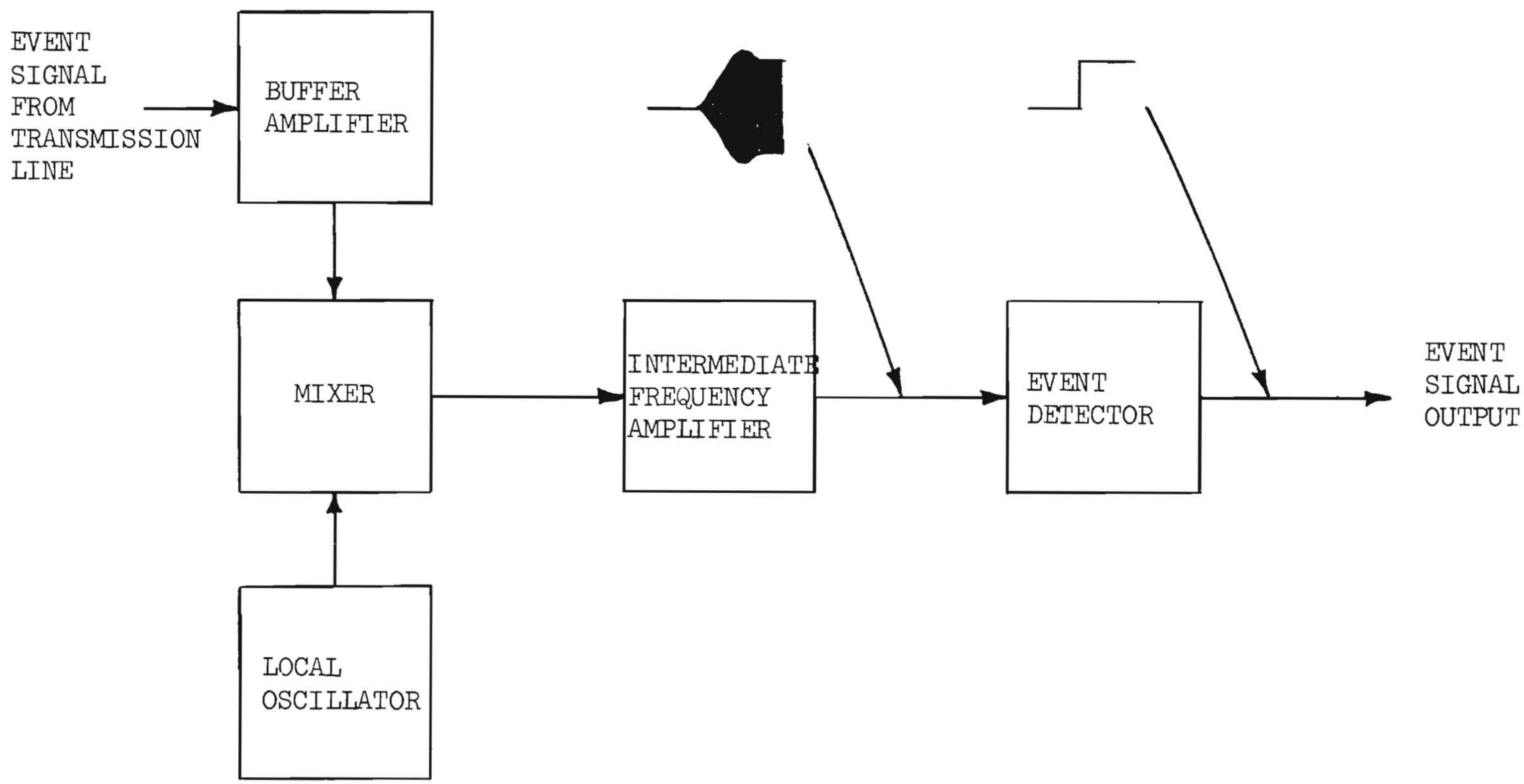


Figure 27. Event Receiver.

receiver of Figure 27 has the advantage of being able to select various channel frequencies by changing only the local oscillator frequency. An event receiver will be needed for each event channel to be received. An incoming line carrying N event signals would be connected to N event receivers. Since the same time and frequency response requirements apply to both event receivers and transmitters, the bandpass filter specifications outlined in Figures 25 and 26 also apply to the receiver IF amplifier.

7. Overall Distribution System

Previous sections have outlined in detail the electrical characteristics of 19 guage twisted-pair lines, and design information for utilizing these lines as event signal carriers has been presented. The purpose of the present section is to make some pertinent observations of (1) the twisted-pair line characteristics, (2) event transmitting and receiving equipment, (3) relative equipment costs, and (4) interface problems. Following these observations, a suggested event distribution system is presented.

It is apparent from Figure 21 that the channel capacity of a single twisted-pair line varies markedly with line length. For example, note that a line length of 6 miles has a capacity of 20 channels while an 8 mile line has a capacity of only 9 channels. Rather than design individual FDM equipment for driving lines that differ in length by only 2 miles, it appears that an economical compromise would be to design FDM equipment for driving a range of line lengths. Such a compromise would provide the additional advantage that some degree of standardization between subsystem components could be accomplished. For example, many of the event transmitters, such as those shown in Figure 23, would have identical operating frequencies.

It was noted in Section III.C.5. that in order to achieve maximum channel capacity, the event signal levels should be proportioned according to the line loss characteristics. If the event signal levels were made equal, some channel capacity would be lost; however, the advantage of less complicated and more flexible FDM equipment would be gained. The decrease in channel capacity for equal level event signals may be estimated from Figures 20 and 21. For example, a 10 mile line has a channel capacity of 7 for proportioned signal levels and a channel capacity of 6 for equal level signals. The minimum power level for equal level FDM signals depends on the highest numbered channel to be used. In the example just described, the minimum power level for 6 channels on a 10 mile line would be approximately 0.53 mw per channel. An equal channel level FDM system also has the advantage that all event channels except the highest one are received with s/n ratios in excess of 20 dB. FDM multiplexing units with equal channel levels could also be used to modulate an RF transmitter. This capability would enhance the flexibility of an equal signal level FDM system.

For long lines which have a capacity of only one channel, no advantage would be gained from using the event transmitter and receiver designed for the FDM system. In a completely wired system, these lines could be driven directly with baseband pulses. Although one line per event would be required, the associated equipment is inexpensive and straight-forward implementation is possible.

Even though all of the above design modifications are achieved with some sacrifice of channel capacity, the corresponding reduction of interface problems and equipment construction problems make these modifications economically worthwhile. Based on these considerations, the system shown in Figures 28 and 29 is suggested as an event distribution system using twisted-pair lines. Note that all of the design ideas discussed are incorporated in this system. Four ranges of line lengths are considered and appropriate event transmitting equipment is used for driving these lines. All event signals for a given distribution range are of the same level, and the FDM equipment associated with each line length is essentially identical except for the number of channels in each unit. Note also that a baseband-pulse system is used for line lengths in excess of 15-1/2 miles. Table II summarizes the design features of the event distribution system of Figures 28 and 29, and Table III indicates the extent of instrumentation of various subsystems of the overall event distribution system.

8. Cost Considerations

Although the event distribution system outlined in Figures 28 and 29 contains no new level of technology with respect to the system components, the total cost for this system is difficult to estimate. The various components, such as event transmitters, event receivers, etc., do not exist as off-the-shelf items. Each would have to be manufactured, and estimating manufacturing costs presents some difficulty event when detailed specifications are available. Such specifications

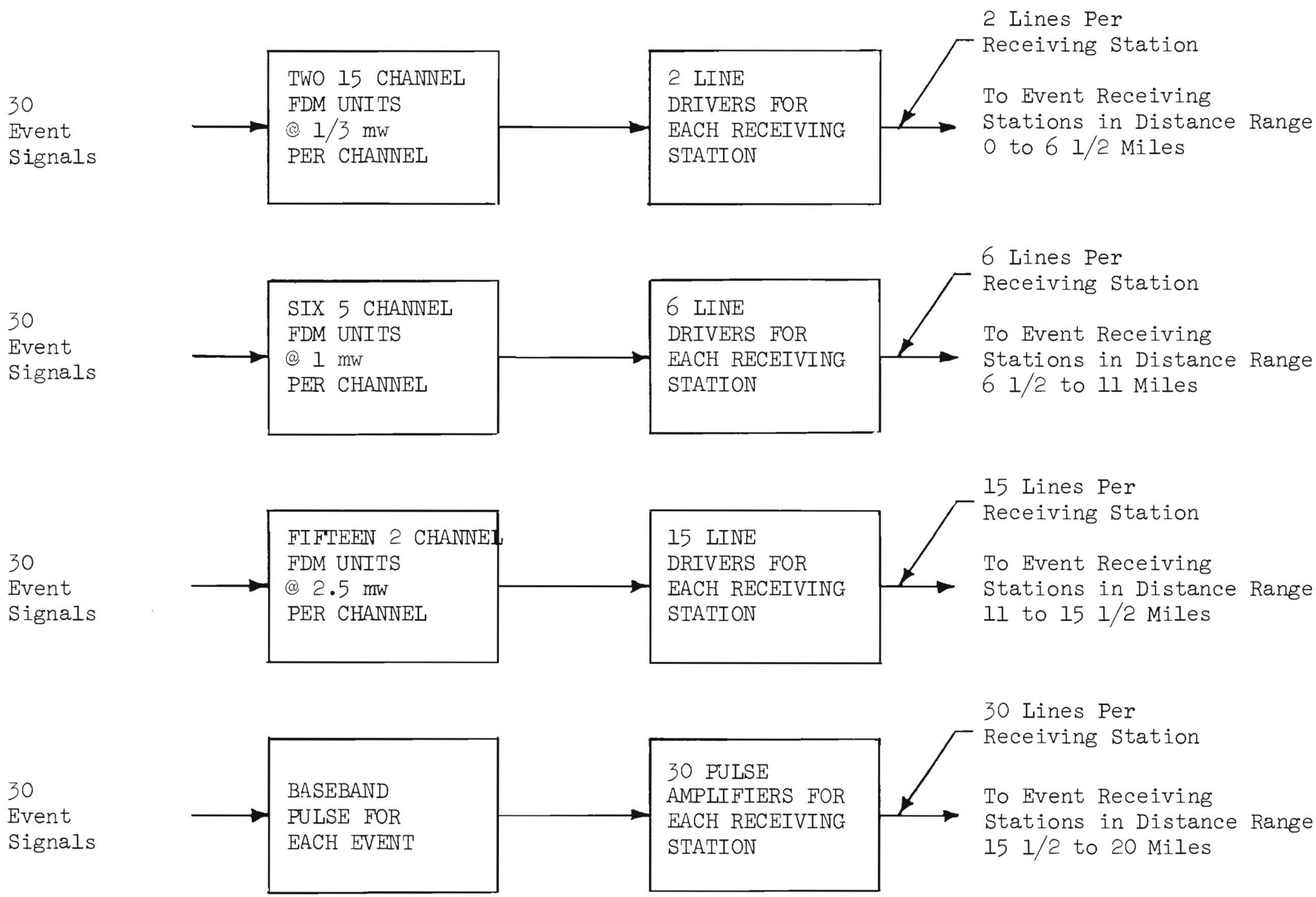


Figure 28. Input end of event distribution system using twisted-pair lines.

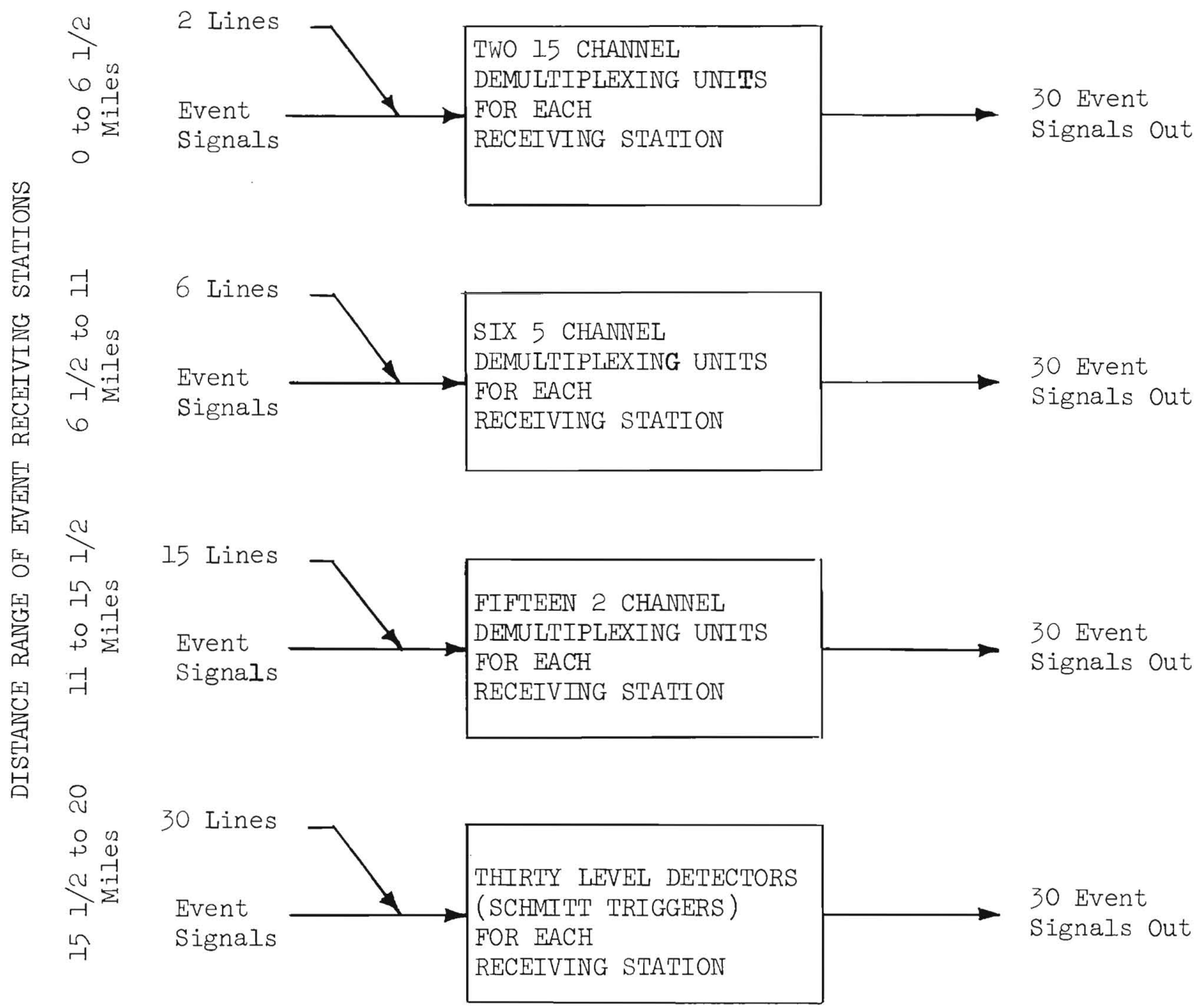


Figure 29. Output end of event distribution system using twisted-pair lines.

TABLE II

SYSTEM REQUIREMENTS TO DISTRIBUTE 30 EVENTS

DISTANCE TO EVENT RECEIVING STATION	0-6 1/2 Miles	6 1/2-11 Miles	11-15 1/2 Miles	15 1/2-20 Miles
TRANSMISSION SYSTEM USED	FREQUENCY DIVISION MULTIPLEXING			BASEBAND PULSE
RECEIVING SYSTEM USED	FDM DEMULTIPLEXING			SCHMITT TRIGGER
NUMBER OF TWISTED PAIR LINES PER RECEIVING STATION	2	6	15	30
NUMBER OF EVENT CHANNELS PER LINE	15	5	2	1
FDM CHANNEL FREQUENCIES	7 + (N-1)8 kHz N = CHANNEL NUMBER			
POWER LEVEL PER CHANNEL	1/3 mw	1 mw	2.5 mw	5 mw
NUMBER OF EVENT TRANSMITTERS REQUIRED PER LINE	15	5	2	NONE
NUMBER OF LINE DRIVERS PER EVENT RECEIVING STATION	2	6	15	30 (Pulse Amplifiers)
NUMBER OF EVENT RECEIVERS PER LINE PER RECEIVING STATION	15	5	2	NONE
NUMBER OF SCHMITT TRIGGER DETECTORS PER RECEIVING STATION	NONE			30

TABLE III

SUBSYSTEM CHARACTERISTICS

SUBSYSTEM	DESCRIPTION
EVENT TRANSMITTER	This device contains a pulse shaper, oscillator, gating circuit, bandpass filter, and a buffer amplifier. Approximately 10 transistors would be used in this circuit.
SIGNAL SUMMING NETWORK	This network may be implemented with either a resistive divider network or a transistorized summing circuit.
LINE DRIVER	The line driver amplifier is basically a balanced output, low gain, low distortion video amplifier. Approximately 5 transistors would be used in this circuit.
PULSE AMPLIFIER	The pulse amplifier is basically a fast risetime, low gain, DC amplifier. Approximately 4 transistors would be used in this amplifier.
EVENT RECEIVER	This subsystem contains a buffer amplifier, oscillator, mixer, IF amplifier, and a detector circuit. Approximately 10 transistors would be used in this device.
LEVEL DETECTOR (SCHMITT TRIGGER)	The level detector could be implemented with a low-level Schmitt Trigger circuit. Three or four transistors are required for this circuit.

cannot be drawn at present; a further development and testing phase would be necessary to produce them.

In spite of these difficulties, an effort was made to produce cost estimates for the various system components. Working from a knowledge of the function and general performance required of each component, tentative circuit diagrams were sketched. From these diagrams, estimates of parts requirements and manufacturing costs were made. The estimates are made on the basis of what a manufacturer might quote to deliver finished components manufactured to detailed specifications by best commercial practice methods, and in quantities sufficient to implement the entire system. These estimated component costs are listed in Table IV. These costs estimates do not include the cost of developing detailed equipment specifications. It should be emphasized that these cost estimates are given only as guideline approximations to the cost of a wire-linked distribution system and as such could be in error. Moreover, these estimates do not reflect the intrinsic cost of twisted-pair lines required for the system.

Also shown in Table IV is the estimated cost of a sample system for distributing 30 events to 20 stations, with five stations falling in each of the distance ranges shown in Figures 28 and 29.

TABLE IV

ESTIMATED SYSTEM COST

Subsystem	Number Required	Estimated Unit Cost
Event Transmitter (FDM)	1 per multiplexed event	$ 250
DC Amplifier (Baseband Pulse)	1 per baseband pulse event per receiving station	25
Line Driver (FDM)	1 per receiving station per FDM line	200
Event Receiver (FDM)	1 per multiplexed event per receiving station	175
Threshold Detector (Baseband Pulse)	1 per baseband pulse event per receiving station	25

Estimated cost of terminal equipment for 30 events and 20 receiving stations, with 5 stations in each distance range shown in Table II. (Does not include cost of development of system or cost of lines) Total Cost $132,000

IV. Radio System

The possibility of using a radio link for an event distribution system was studied. The study covered two different frequency bands, the millimeter wave region and the X-band region. In general, it was found that components for the RF portion of the systems are readily available as off-the-shelf items. The major difficulty is that suitable multiplexing equipment is not readily available. A tentative design for a suitable multiplex unit was developed and tested on a limited scale. The two radio systems and the multiplex studies are discussed in the following sections.

A. Microwave Link at 35 GHz

The frequency region near 35 GHz is attractive from a standpoint of system implementation for several reasons, including the fact that interference with other services is likely to be less than that expected at lower radio frequencies. Components are readily available and are both small and lightweight so that systems can be compact even though they have highly directional antennas. Sources have been developea which offer reasonable output power and good stability so that no elaborate receiver systems are required to achieve operating characteristics competitive with lower frequency systems. The greatest single disadvantage for a line-of-sight 35 GHz system is centered about the relatively high absorption of radiation above about 18 GHz by the water vapor molecule. This absorption could impair the operation of the system during adverse weather conditions. However, under good weather conditions the absorption is unlikely to be large enough to seriously affect transmission over path lengths of 20 miles or less.

In embarking on system estimates concerning the RF portion of the transmitter and receiver assembly it is suggested that consideration be given to the Scientific-Atlanta Model 22-1 one foot diameter parabolic antenna with Model 23-26/1 feed as the primary link antenna. At a frequency of 34.9 GHz, this antenna has a gain of approximately 38 dB and a maximum beamwidth of 2.5°. With such a narrow beamwidth a separate antenna and feed would be required to point to each remote station. Standard rectangular waveguide for the 35 GHz range is WR-28/RG-96/u with inside dimensions 0.280 x 0.140 inch. At 34.9 GHz the theoretical attenuation is about 0.16 dB/foot for this size waveguide. It is thus desirable to keep waveguide runs as short as possible.

Because it is desired to transmit only a simple step function type signal with a rise time of less than 1 msec it is reasonable to assume that a given signal will require no more than 10 kHz bandwidth. If 5 kHz is allowed for guard bands between channels, then thirty channels will require only 450 kHz modulation bandwidth in the receiving system or on the chosen carrier generator. If a receiver noise bandwidth of 1 MHz is assumed, operative under a normal temperature environment near 290° K, a sensitivity of -105 dbm can be obtained with a balanced mixer using diodes such as the Sylvania D5253C and an IF amplifier having a noise figure of 1.5 dB. This implies that a maximum receiver noise figure of 9 dB can be achieved at 34.9 GHz as cited by recent Sylvania data sheets.

Distances from the transmitter to the various receiving points are likely to vary from 4 to 20 miles. The path loss as a function of distance is shown in Figure 30 for 34.9 GHz, exclusive of any losses due to molecular absorption.

The transmitter power for a required receiver output signal/noise ratio may be calculated from

$$10 \log \frac{P_t}{P_r} = A_p + \frac{S}{N} + (nf) - G_t - G_r + A_w + A_a \quad , \tag{6}$$

where P_t is the transmitter power,

A_p is the path loss in dB,

$\frac{S}{N}$ is the desired signal-to-noise ration in dB,

(nf) is the receiver noise figure,

G_t is the transmitting antenna gain in dB,

G_r is the receiving antenna gain in dB,

A_w is the waveguide system loss between the signal source and antenna in dB,

A_a is the atmospheric loss in dB from molecular absorption, and

P_r is the noise power in the receiver.

A 30 dB signal-to-noise ratio should yield a signal relatively free of effects of fading and, as will be seen later, give some protection from deleterious weather conditions. For an eight mile path using the parameters mentioned earlier we have

$A_p = 145.7$ dB,

$$\frac{S}{N} = 30 \text{ dB},$$

$$(nf) = 9 \text{ dB},$$

$$G_t = 38 \text{ dB},$$

$$G_r = 38 \text{ dB},$$

$A_w = 0.3$ dB (assume a two foot waveguide run),

$A_a = 1.6$ dB (assume 18° C, 760 mm Hg, 66% humidity), and

$P_r = 4 \times 10^{-15}$ watts for 1 MHz bandwidth,

from which

$$P_t = 4.6 \times 10^{-3} \text{ watts} \quad . \tag{7}$$

For a twenty mile path using the same equipment parameters and weather

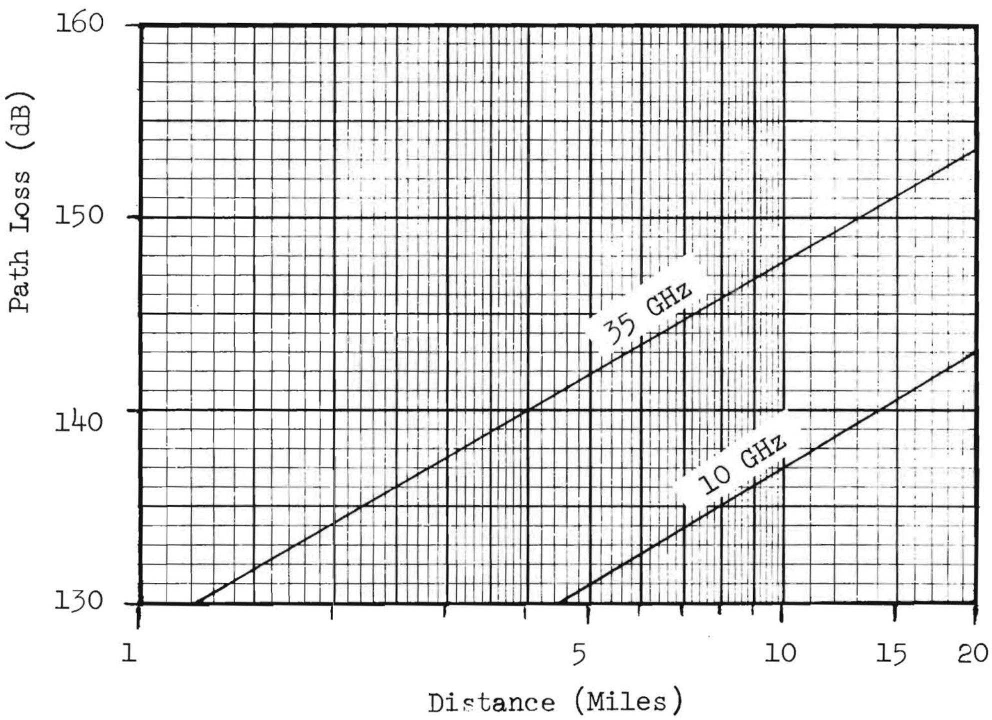


Figure 30. Free space loss at 10 GHz and 35 GHz.

conditions as for the above eight mile calculation, one obtains

$$P_t = 59 \times 10^{-3} \text{ watts} \quad , \tag{8}$$

where $A_a = 4$ dB, and

$A_p = 153.6$ dB.

With these figures as a reference, it is useful to consider additional components for the system. Oscillator tubes are relatively inexpensive for the 35 GHz range if power requirements are of the order of 100 mw or less. For tubes with higher output, the cost is considerably greater whether an output of one or ten watts is generated. An OKI 34LV20 tube has a guaranteed output of 10 watts with a typical output of 20 watts. Even with 20 different receiving stations and with transmitter/antenna waveguide runs longer than two feet, it would be possible to transmit 10 dB more power than the systems calculations require for the 30 dB signal-to-noise ratio to each receiver by using this tube as a central transmitter. This 40 dB signal-to-noise ratio should yield better than 99.99% reliability against fade during ideal weather, and should also permit satisfactory operation during somewhat poorer conditions.

Atmospheric absorption near 35 GHz occurs because of the resonances of rotational energy transition associated with the strong electric dipole moment of the water vapor molecule and the weak magnetic moment of the oxygen molecule. Water vapor has literally hundreds of these resonance absorptions occuring at frequencies from 22.3 GHz to the infrared region. The observed absorption spectrum of oxygen is more limited; it is characterized by a cluster of more than twenty lines near 60 GHz and a single line near 120 GHz. Both the water vapor and oxygen lines are pressure broadened so that there are broad attenuation skirts which add collectively to give a measureable value of attenuation for frequencies far removed from the centers of the resonance. The 22.3 GHz water vapor skirt attenuation and 60 GHz oxygen skirt attenuation yield a minimum sum at 34.9 GHz. Therefore, for frequencies above 20 GHz, terrestial systems are best implemented at 34.9 GHz if minimum transmission path loss in clear humid air is a requisite.

Rain does not yield a broadened line type spectrum such as is characteristic of atmospheric water vapor but rather results in an absorption which simply increases with increasing frequency. Table V

TABLE V

ATMOSPHERIC ATTENUATION OF 34.9 GHz and 10 GHz RADIATION AS A FUNCTION OF RAINFALL RATE

Rainfall Rate (mm/hour)	Attenuation (dB/mile) 34.9 GHz	10 GHz
0.25 (drizzle)	0.1	0.003
1.0 (light rain)	0.4	0.05
4.0 (moderate rain)	1.7	0.1
16.0 (heavy rain)	6.9	0.8

shows the approximate attenuation experienced at 34.9 GHz as a function of rainfall rate. It is apparent from this table that in light rain it will be possible to maintain a 30 dB signal-to-noise ratio over all parts of the link, which would still give better than 99.9% reliability against fading over all paths. For moderate rain a 20 dB signal-to-noise ratio can be maintained over the shorter paths which gives better than 99% reliability against fading although the 20 mile paths could be anticipated to be only about 90% reliable under these conditions. If heavy rain prevails over the whole area, then the 35 GHz system could not be expected to function as a useful data link. These are worst case conditions, and it is expected that launches would seldom take place when there was a moderate or heavy rain cover over the whole area. Localized showers, of course, only affect certain portions of the link, and the attenuation would be proportionately less, depending on the extent of the precipitation.

The absorption due to atmospheric fogs is best stated in terms of visibility at 20° C. For a visibility of 1000 feet, the attenuation at 34.9 GHz is 0.1 dB/mile. The reliability of the system is thus not likely to be impaired for any fog which gives sufficient visibility to launch a missile.

If one assumes that twenty receiving stations are required then costs for the microwave portion of the system may be estimated as follows:

Quantity	Item	Each	Total
40	Antennas, Scientific-Atlanta 22-1, with 23-26/1 feed and mounting	$ 540	$21600
1	Transmitter Klystron OKI 34LV20	3700	3700
20	Receiver L. O. Klystrons OKI 35V30	825	16500
1	HV Klystron Supply Narda 62A1	1300	1300
20	LV Klystron Supply Weinschel Z819	675	13500
20	Balanced Mixers with Crystals	500	10000
20	Fixed Attenuators	85	1700
20	Isolators	500	10000
20	1 MHz BW 1.5 dB NF IF Strips	350	7000
1	High Power Isolator	1100	1100
19	Power Dividers	160	3050
	Waveguide, flanges, antenna tower, hardware for connecting and mounting, miscellaneous.		5000
	Total		$94450

The block diagrams of Figure 31 illustrate how these components would be assembled in order to achieve an operational system.

From an operational point-of-view, it is obvious that a 35 GHz link can be assembled readily from "off-the-shelf" components with reasonable performance characteristics. It must, however, be remembered that the system will, even at 99.99% reliability over the twenty-mile link, not be as reliable as a wire or coaxial link which are immune to fading. Under adverse weather conditions it has been shown that the reliability is likely to be lower than 99.99% and completely unusable in a heavy

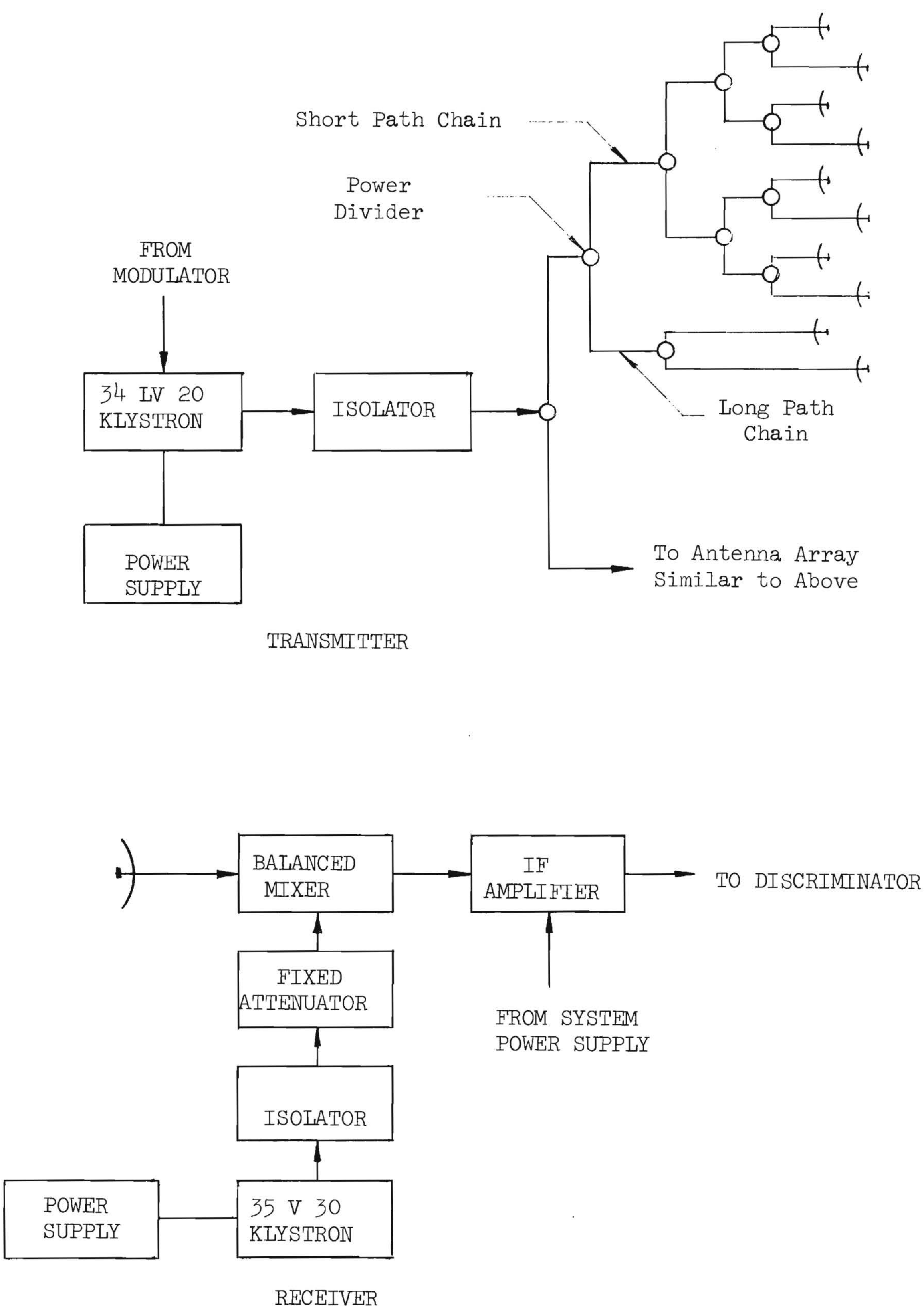


Figure 31. Block diagram of RF portion of 35 GHz system.

storm. Maintenance costs are likely to be greater with this system than with a directly connected system. Klystrons may be expected to have a lifetime of 1000 hours (some will last in excess of 10000 hours). The addition of Klystron power supplies, IF strips, etc., simply means more system variables to be concerned about. On the positive side, however, the system would represent a useful implementation of a portion of the spectrum that is on the frontier of technology. It would be tremendously versatile in that the transmitter would have a bandwidth of 100-200 MHz, meaning that with some modifications the system would be capable of handling hundreds of information channels in the future. The cost per microwave station averages out to less than $5000 which is very competitive with the purchase price of coaxial cable exclusive of laying costs which would be greater than the assembly costs of the 35 GHz hardware.

B. Microwave Link at X-Band

A system using X-band components at 10 GHz center frequency could be implemented with performance closely resembling that discussed for the 35 GHz system by simply increasing the antenna diameter to two feet. An improvement in receiver sensitivity of 2.5 dB would be obtained by using the Sylvania 1N53GM mixer diodes. X-band waveguide is 0.4 by 0.9 inch in cross-section and is denoted by WR-90/RG-52/u. The path loss for 10 GHz is, of course, less as is shown on the graph of Figure 30. This allows the use of lower gain antennas for the X-band system. Atmospheric attenuation is only 0.025 dB/mile at 10 GHz so is not nearly as important in systems calculations. Attenuation due to precipitation is not as important as at 35 GHz as is shown in Table V. Measured data on fogs were not available for X-band but will be less than the 0.1 dB/mile cited for 35 GHz.

The rationale for implementing the 35 GHz stations may be pursued for the 10 GHz system with cost estimates as follows:

Quantity	Item	Each	Total
40	Antennas, Scientific-Atlanta 22-2, with 23-8.2/2 feed and mounting	$ 610	$24400
1	Transmitter Klystron	2500	2500
20	Receiver Local Oscillator Klystron (Varian VA-218)	160	3200
1	HV Klystron Supply	2500	2500
20	LV Klystron Supply Weinschel Z816B	650	13000
20	Balanced Mixers with Crystals	300	6000
20	Fixed Attenuators	60	1200
20	Isolators	120	2400
20	1 MHz BW 1.5 dB NF IF Strips	350	7000
1	High Power Isolator	200	200
19	Power Dividers	75	1425
	Miscellaneous Hardware		7000
	Total		$70825

C. Multiplexing Techniques

The purpose of the microwave transmission links described in the preceding sections is to distribute information arising at LCC to approximately twenty receiving stations with a timelag less than 1 msec.

It is the purpose of this section to discuss various ways to code this information onto the transmitting source, and to decode the information at the receiving station. Estimates will be based on providing 30 event channels to allow for both future growth and additions to the present system.

Many techniques have been conceived to transmit multi-channel information from one place to another. The most popular technique for the transmission of voice and television information is the SSB-FM multiplex system used by the Bell Telephone Company. Their basic circuit, called the A-Type channel bank, is a 12 channel solid state SSB multiplexer. A ring type modulator impresses the voice information onto a subcarrier oscillator. The lower sideband is then selected by a crystal bandpass filter and is added algebraically to 11 other similar signals with different subcarrier frequencies. This output is fed into a baseband amplifier which may be used to feed the particular type of transmission circuit that is to be used. Similar units are commercially available up to about 15 channels. Bell System uses 50 of these basic units in conjunction with subgroup and supergroup modulators to achieve a 600 channel microwave communications link.

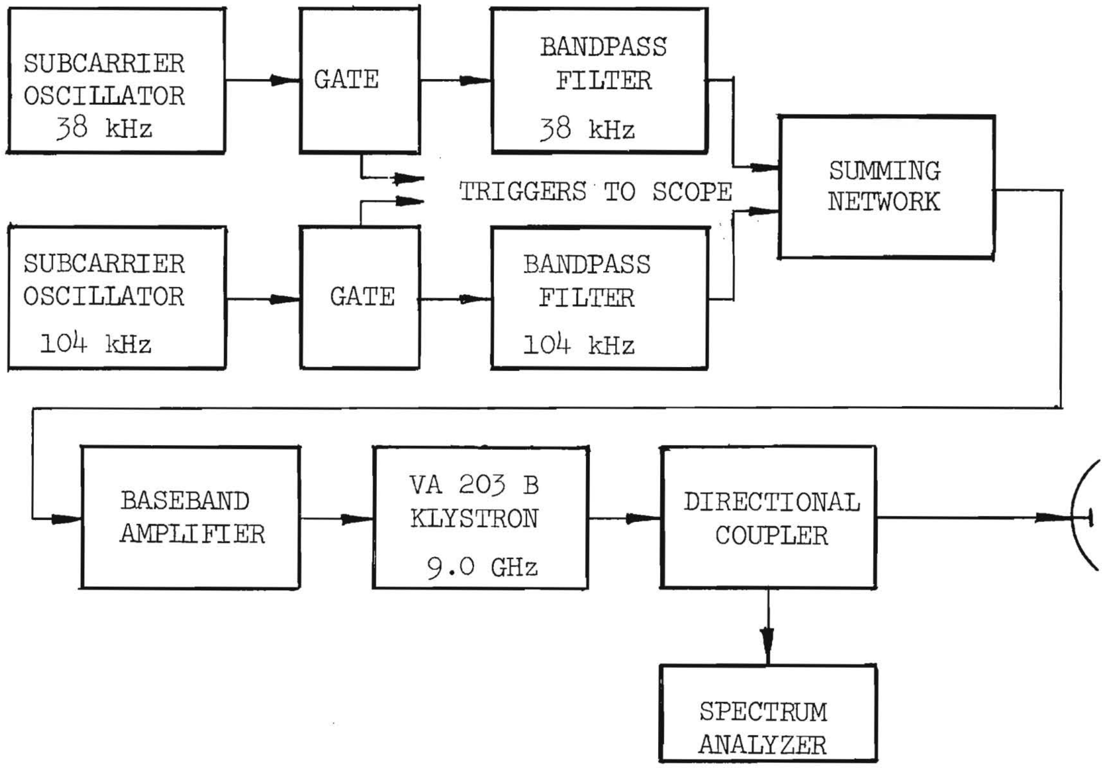
Six commercial firms active primarily in the field of communications and telemetry systems were contacted for information concerning selection of optimum components for the event multiplexing circuits. Although detailed information and specifications were furnished, most firms were more interested in furnishing a bid on a complete communication system than in providing information on individual component selection, which could be utilized directly for a microwave system implementation.

Armed with the available specifications of a number of multiplexing systems, it was decided that none of the commercial systems were really optimum because of bandwidth limitations, or cost and complexity considerations. For most SSB multiplexers, the 3 kHz telephone type bandwidth is marginal, and the response does not extend to DC on the low frequency end because of the bandwidth of the carrier suppression filter.

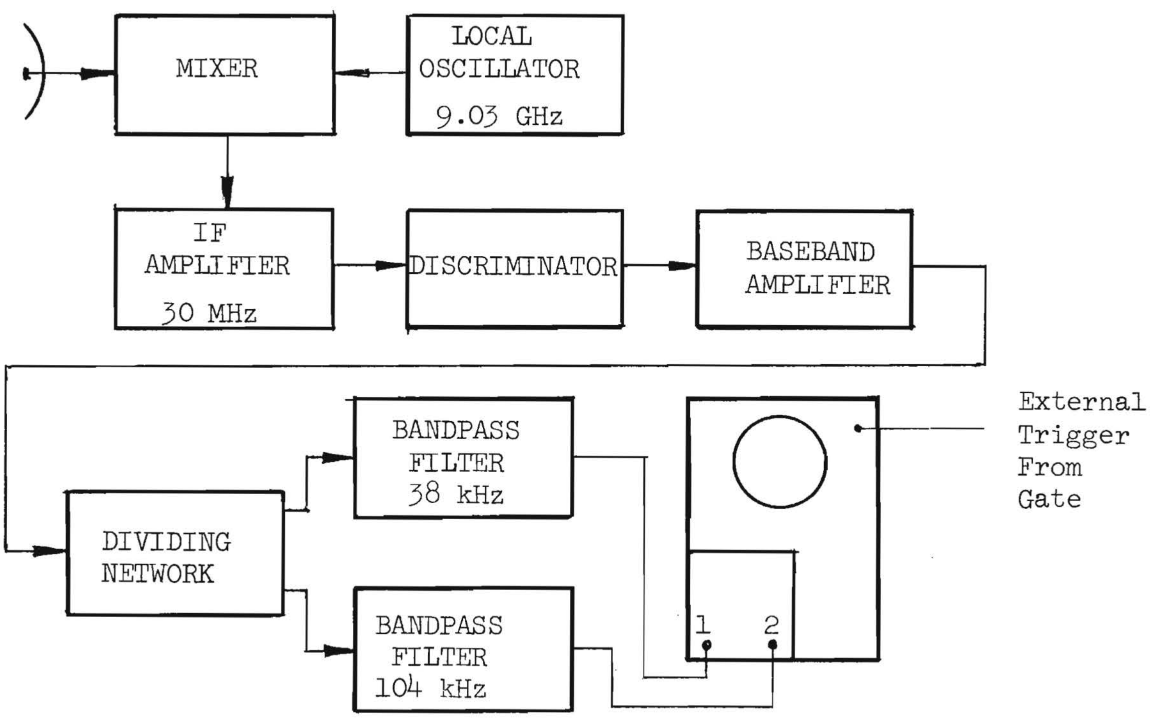
Since the information to be transmitted is simply a "yes" or "no" message indicating the event has either taken place or has not taken place, a much simpler multiplexing scheme than those commercially available can be used. This scheme would basically consist of one subcarrier channel for each event to be monitored with provisions for gating the channel on and demodulating the appropriate sideband with a time delay equal to or less than 1 msec.

A two-channel multiplexing link was set up the laboratory to evaluate the overall applicability of the above scheme to transmission of event markers, and to determine some general system parameters that would provide a basis for a realistic proposal of a practical system. Since the parameters to be determined were all functions of the multiplexing and demodulation equipment, it was decided to use an X-band carrier system to implement the link because of the abundance of X-band components available in the laboratory, and the lack of components available at 35 GHz. It will be noted that the 100 MHz modulation bandwidth provided by the OKl type 34LV20 Klystron, which was proposed as the 35 GHz transmitting source in Section A, compares favorably with the VA-203 X-band Klystron used as the transmitting source in the test link. Since the total line delay is a function of the path length only for a given microwave transmission system, and the modulation bandwidths of the two sources are comparable, the results of these tests are as applicable to 35 GHz systems as they are to X-band systems.

A block diagram of the experimental set-up is shown in Figure 32. The two subcarrier oscillators at 38 and 104 kHz were each passed through a diode bridge gate, a bandpass filter, and then into a summing network. The output of the summing network was applied through a base-band amplifier onto the reflector electrode of the VA 203 X-band Klystron. The two filters provided 30 dB of isolation at the cross-over point while the diode gate provided about 25 dB of rejection in the "off" position. Linear detection in the receiver was provided by a level of modulation which yielded a spectral width of about 600 kHz as measured by the spectrum analyzer connected through a directional coupler to the output of the transmitting Klystron. Figure 33(a) shows a photograph of the spectrum taken on the analyzer oscilloscope display with the level of the 104 kHz sidebands increased slightly for recognition. The spectral width is approximately 500 kHz and the response is logarithmic. The unequal spacing of the left and right sidebands is due to the slow drift and jitter of the unstabilized Klystron. Figure 33(b) shows another spectral photograph taken with linear response showing only the 38 and 104 kHz first order sidebands.

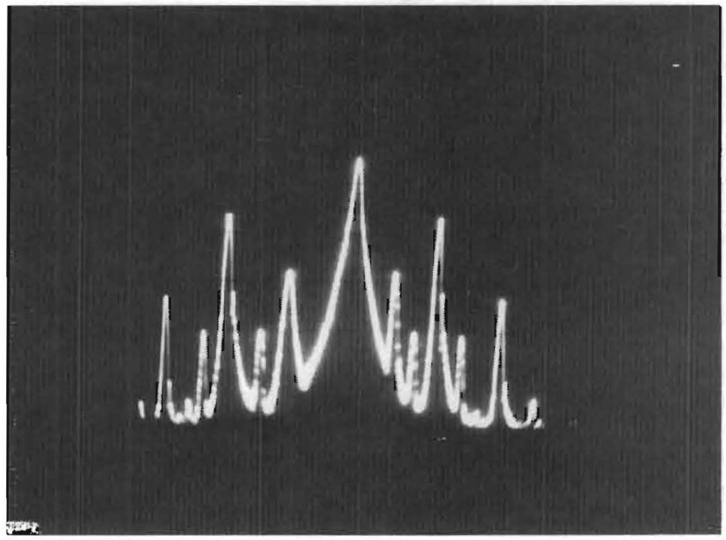


TRANSMITTER

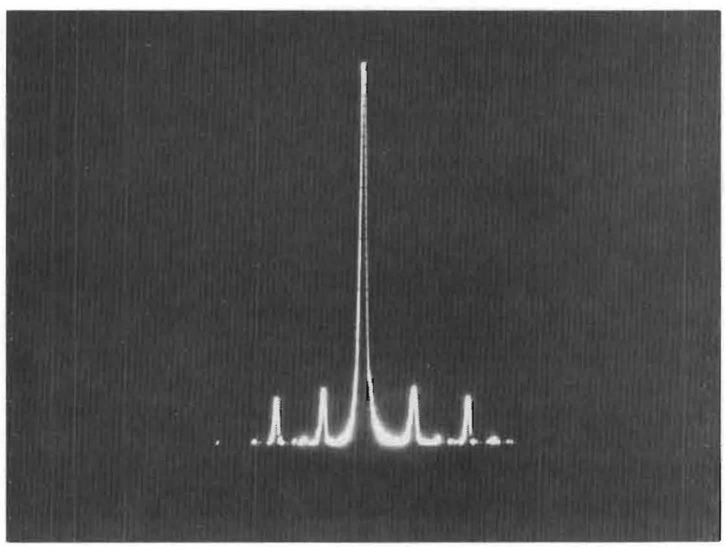


RECEIVER

Figure 32. Laboratory set-up for multiplex experiments.



(a) Logarithmic Display.



(b) Linear Display.

Figure 33. Spectrum of Transmitter Output with 38kHz and 104kHz Subcarriers Present.

The two subcarrier signals are demodulated in a standard superheterodyne receiver consisting of a mixer, local oscillator, 30 MHz IF amplifier, and ratio detector. After demodulation, the two signals are amplified by a baseband amplifier and separated through two bandpass filters tuned to the subcarrier frequencies. The outputs of the two filters are applied to a dual channel oscilloscope to provide a simultaneous display of the two signals. Figure 34(a) shows a final trace photograph of the demodulated 38 and 104 kHz subcarrier signals.

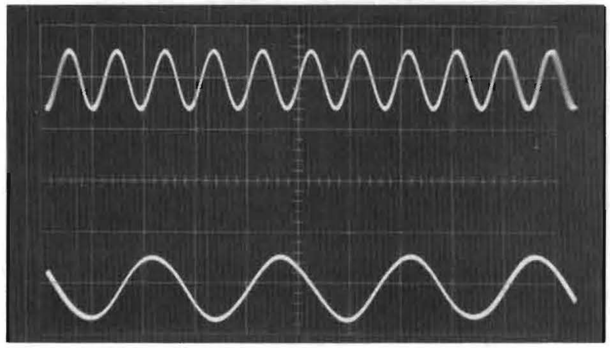
The time delay between gating the subcarrier signal on (event has occurred-initiated at the transmitting site), and receiving the subcarrier at the output of the receiver bandpass filter (indication that the event has occurred-measured at the receiving station) was measured in the following manner:

(1) The oscilloscope in Figure 32 was set up for single sweep operation with either subcarrier signal as input to the vertical amplifier on the scope.

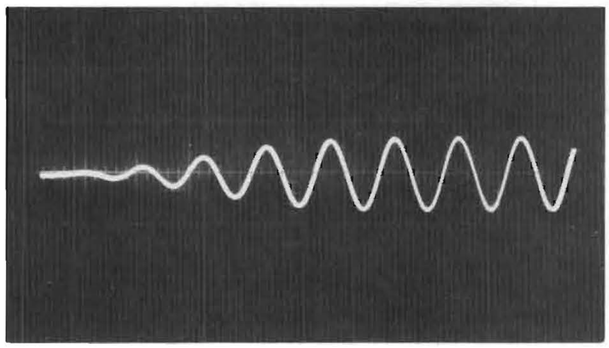
(2) The horizontal sweep controls were set so that the triggering voltage which is initiated simultaneously with the "on" gate was sufficient to trigger a single sweep.

(3) With the gate in the "off" position and the single sweep "armed", the shutter on the oscilloscope camera was opened and the gate switched to "on".

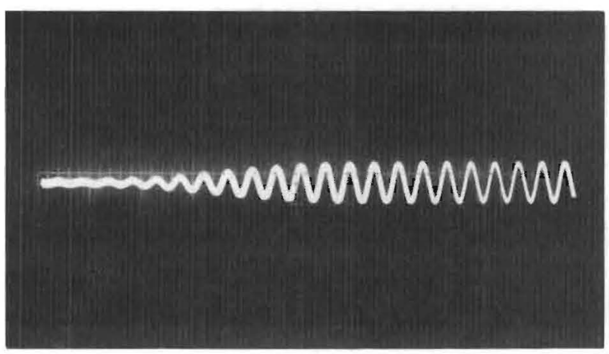
The resulting build-up of the subcarrier signals is shown in Figure 34(b) and 34(c) for the 38 and 104 kHz frequencies, respectively. In either case, the total width of the display represents 200 μsec. It is apparent that the build-up time for both signals is about 100 μsec. Since the free space transmission path used in the experimental set-up



(a) Both Signals Present.



(b) Build-up of 38kHz Signal (Full Sweep 200μsec.).



(c) Build-up of 104kHz Signal (Full Sweep 200μsec.).

Figure 34. Oscilloscope Display of Output Signals.

was only several feet long, this time delay is due only to the electronic circuitry, and the total time delay would include the propagation path delay of the radio frequency carrier wave. It may be noted that even for a 20 mile path length, the propagation delay is only about 120 μsec, bringing the total time delay up to about 250 μsec. Since the end use of the event signal has not been clearly defined, no processing of the subcarrier signals was provided after separation.

A cost estimate of the components for transmitting multiplex equipment would break down as follows:

	Item	Cost
(1)	Crystal Controlled Subcarrier Oscillator	100
(2)	Crystal Bandpass Filter	250
(3)	Gate and Summing Networks	50
(4)	Baseband Amplifier	200

A 30 channel transmitting station would consist of:

Quantity	Item	Each	Total
30	Subcarrier Oscillator	100	3000
30	Bandpass Filter	250	7500
30	Gate	50	1500
1	Baseband Amplifier	200	200
	Total		12200

Since only one baseband amplifier is needed regardless of the number of channels (provided the amplifier bandpass is sufficiently broad to include all channel frequencies) the per channel cost of the transmitting station is approximately 400 dollars.

Demultiplexing equipment for the receiving station would include:

	Item	Cost
(1)	Baseband Amplifier	200
(2)	Crystal Bandpass Filter	250
(3)	Signal Processing Electronics	50

A 30 channel receiving station would include:

Quantity	Item	Cost	Total
1	Baseband Amplifier	200	200
30	Bandpass Filter	250	7500
30	Signal Processing Electronics	50	1500
	Total		9200

The per channel cost per receiving station would be approximately 300 dollars. A total component cost for 30 channel system with twenty receiving stations, including the 35 GHz microwave carrier system, should be about $280,000.

The experimental two channel event transmission link has clearly demonstrated the feasibility of utilizing the simple frequency multiplexing scheme described above for transmitting event markers on a microwave carrier to receiving stations within a twenty mile radius of the point of origin. It was shown that the maximum time delay is less than 250 μsec, and 30 dB of channel isolation could easily be obtained.

The broad modulation band of either the 35 GHz Klystron of the X-band Klystron would easily provide for several hundred event channels if the need arose. While the baseband amplifier, bandpass filters, and sub-carrier oscillators could probably be purchased as more or less off-the-shelf stock items, a reasonable amount of design and development would be needed to realize the gate and summing circuits in the transmitting complex and the dividing network and signal processing in the receiving stations.

V. Coaxial Line System

A study of coaxial lines was made to determine the feasibility of implementing a wired system using coaxial lines. This study was quite limited since it quickly became apparent that the cost of such a system would be prohibitively high.

A coaxial cable system would differ from a radio system conceptionally only in that the signals would be transmitted over cable rather than be radiated between antennas. The need for multiplexing equipment similar to that discussed for the radio system would still exist. Hence, in comparing a coaxial system with a radio link, only the RF portion of the radio system should be considered.

The main advantage that a wired system using coaxial cable would offer over a wired system using twisted-pair would be the ability to transmit all event signals over a single cable afforded by the wide bandwidth of coaxial cable. To take advantage of this ability, a carrier frequency high enough to permit sufficient modulation bandwidth would be required. A minimum frequency of several hundred kHz, perhaps even 1 MHz, would be needed for the carrier.

Examination of attenuation data for cables showed that even at this low frequency a fairly large (and expensive) cable would be required unless repeaters were used. Also, it is desired, if not required, by KSC that repeaters not be used.

Although many factors related to the construction of a cable affect its attenuation characteristics, one of the dominant factors is simply physical size of the cable. To reduce the attenuation low enough to deliver a usable signal at the end of a 20 mile path would require a low loss cable over 1/2 inch in diameter. Commercially available cables of this type cost in excess of $.50 per foot, thus the cable cost alone for a 20 mile path would exceed $50,000 if readily available cable were used. However, since NASA requires that cables be buried and that only lead-sheathed waterproof cables be used, suitable cable could be obtained only on special order and probably at a far higher cost. In addition, the cost of installation would have to be added, and the multiplexing equipment constructed.

In view of these estimates of high cost, and also because a coaxial cable system would seem to offer little or no advantage over the systems previously discussed, consideration of the coaxial cable system was dropped.

VI. Optical Telemetry Link

A discussion of telemetry systems would not be complete without some mention of the techniques of data transmission over optical carrier waves. In view of its wide modulation bandwidth, the use of an optical carrier is very attractive for systems requiring extremely high data rate and handling capability. The advent of the laser has provided a means of generating and launching a coherent optical carrier in a configuration which is extremely compact when compared to a microwave transmitter. In addition, the short optical wavelength allows the laser to launch a beam whose divergence is small enough to keep diffraction losses to a minimum over transmission paths up to several miles in length. These advantages, along with the large modulation bandwidth afforded by the optical carrier, have prompted the prediction of an increasingly important role for the laser in the envolvement of future telemetry systems. It should be pointed out, however, that as yet the state-of-the-art has not advanced sufficiently to allow the optical telemetry system to compete with the microwave or wire carrier system on a direct replacement basis for the type of data transmission considered in this report.

A comparison of the laser with the typical microwave generator will illustrate some of the advantages and disadvantages peculiar to each system. The typical optical laser has a beam divergence ranging from about 0.5 to 1.0 milliradians, and a beam diameter of about 2.0 millimeters. Beam expanding optics can be employed to increase the beam diameter to about 50 millimeters and reduce the divergence by a factor of about 25. An optical laser equipped with a beam expander can be used over a path length of about 2,000 meters with negligible diffraction loss. By comparison, the diameter of a parabolic reflector at 35 GHz necessary to give a beam divergence of 1.0 milliradians is about 35 feet, and a reflector equivalent to the expanded optical beam would measure about 900 feet. Hence, for an equivalent received power level, it would appear that the power output of an optical laser could be reduced considerably from that required from the microwave transmitter. If the proper atmospheric conditions over the free space path exist and an equivalent signal-to-noise ratio in the optical receiver is required, this would, indeed, be the case.

While the microwave carrier system can be designed to operate with high reliability over a wide range of atmospheric conditions, the optical carrier system is limited almost completely to optimum atmospheric conditions for transmission paths exceeding a few tens of feet. The short wavelength and narrow beam characteristic of the laser transmitter give rise to additional transmission loss phenomena which are usually negligible at the microwave frequencies. The attenuation of a microwave signal in rain and fog is due primarily to pressure broadened molecular absorption by water vapor and oxygen. The primary attenuation phenomena affecting an optical signal is scattering by water droplets. These droplets range in size from several microns to over 100 μ in fog, and typically greater than 100 μ in rain. Thus, the scattering of the optical carrier ($\lambda \approx 0.7\ \mu$) in fog follows the Mie scattering theory for the smaller droplets and the optical scattering theory for the larger droplets. A 35 GHz carrier by comparison has a wavelength of 8600 μ and follows the Rayleigh Law (scattering cross-section proportional to one over the fourth power of the wavelength) for droplets less than about 1000 μ in diameter. Absorption coefficients as high as 250 dB per centimeter have been observed at the optical wavelengths in heavy rain. Even moderate rainfall and light fog can completely attenuate an optical carrier generated by the most powerful laser yet developed over a path length of 5 to 25 miles.

Recent experiments with laser range-finding devices have uncovered another serious optical transmission problem caused by atmospheric pressure gradients near the earth's surface. An optical carrier passing through a transmission medium of varying pressure or density will usually be refracted in a varying and unpredictable manner. One possible cause of local variations in atmospheric density is heat reflected from certain types of terrain such as large areas of sand or smooth man-made surfaces. An optical beam passing over such terrain is likely to be refracted and result in a severe pointing and alignment problem between transmitter and receiver.

The scattering phenomena and the pointing problem discussed above can be eliminated almost entirely by employing a light guide instead of the free-space transmission medium, or it can be partially eliminated by going to a longer wavelength coherent source. Recent developments in laser research have resulted in the successful operation of gaseous lasers at wavelengths down to about 400 μ. A carbon dioxide laser operating at 10.6 μ with a continuous power output of one kilowatt has been developed by Raytheon. Recent experiments both in England and the U. S. have shown that molecular gases employing water vapor or some of the volatile cyanide compounds will lase at frequencies between 20 and 400 microns. The cw output power from these devices operating at the longer wavelengths is still very low, typically 1 to 10 microwatts. While the use of longer wavelength lasers would tend to reduce the scattering and pointing problems mentioned above, a sacrifice in size and data carrying capacity would result. For example, the Raytheon CO_2 laser utilizes a folded 20 meter long 4 inch diameter discharge tube to achieve a continuous power output of one kilowatt. It would also be necessary to pick a frequency coinciding with one of the few atmospheric transmission windows available for this region so that molecular absorption could be minimized.

We have thus far discussed only the generating part of a laser telemetry system. As would be expected, other problems arise with the receiver and modulator.

Electro-optic modulators with a maximum bandwidth of 10 GHz are currently available as off-the-shelf items. The type device most commonly employed is the Pockel's Cell modulator which uses a nonlinear crystal such as KDP (Potassium Dihydrogen Phosphate). The bandwidth of this type of modulator is limited to about 10 GHz by the dielectric loss in the crystal. Thus, the modulation bandwidth of the laser is limited by the external modulating device.

Receivers can also be assembled from off-the-shelf components.

Direct detection can be accomplished with a photomultiplier tube or one of the many semiconductor configurations available. The back-biased semiconductor junction is usually preferred because of its high quantum efficiency and broad bandwidth (typically 2-20 GHz). A superheterodyne type receiver has been designed around a local oscillator-mixer configuration developed by Siegman at Standord University. Siegman's device uses a photocathode mixer coupled to a traveling wave tube to convert the received optical carrier to a microwave IF frequency.

For transmission over ranges of less than 100 miles, the signal-to-noise ratio required in the optical receiver compares favorably with that of the microwave receiver. In the optical receiver, however, one has several sources of noise other than thermal noise. The noise caused by random fluctuations of high energy photons can exceed the thermal noise for low noise temperatures. In addition, sunlight, ambient light in the receiver environment, and wideband infrared radiation from hot objects can contribute to the noise level. Although the narrow acceptance angle of the receiver optics usually eliminates most of this external noise, the noise level in the receiver is still higher than that in a microwave receiver.

In view of its obvious advantages, it seems likely that the optical carrier system will occupy an important role in telemetry systems of the future. Whether or not this role will be one of general replacement of other telemetry systems is highly questionable in view of the many problems enumerated in this short discussion.

The problem of achieving high reliability of data transmission over a free-space path of 5 to 25 miles with an optical carrier system would be insurmountable at the present time. It is possible that a light guide could be used to alleviate the problems associated with free-space transmission; however, in view of the moderately low data rate considered for the event distribution system, it is felt that the optical carrier system is far too complex and uncertain to be considered seriously at this time.

VII. Conclusions and Recommendations

Five different transmission systems have been investigated to determine their relative merits for distributing up to 30 binary signals to 20 remote sites at distances up to 20 miles within 1 millisecond. The five systems reviewed utilized (1) twisted-pair lines, (2) millimeter wave radio, (3) X-band radio, (4) coaxial lines, and (5) laser beam. Two possible system configurations using twisted-pair line were discussed.

All of these systems except one (which would use one line per event) will require some form of multiplexing to combine multiple signals into one transmission channel. Frequency division multiplex seems to be best suited to the problem in view of the asynchronous nature of the signals and overall time requirement for event distribution, and this form of multiplexing is recommended. An effort to locate suitable multiplex equipment in off-the-shelf form was unsuccessful. Study of the problem indicates that there should be no large technical problem in designing and building multiplexing equipment, especially since the binary character of the signals will lend itself to a simplified version of frequency division multiplex in that the subcarriers will not require modulation.

As for the various methods of transmission, all five appear to be capable of meeting the system requirements. Also, all except the laser beam could easily be implemented within the limits of existing technology; even the laser cannot be definitely ruled out as beyond the state-of-the-art, but in view of the many problems as yet unresolved in laser technology, further consideration of lasers is not recommended.

It is also recommended that the coaxial line system be dropped from consideration. A single coaxial line could provide a bandwidth sufficient to carry all of the event signals; also it would possess an advantage over a radio system in that energy would not be radiated into the environment. However, the high cost of installing a coaxial line makes the system unattractive.

All of the remaining systems, two radio systems and two different implementations using twisted-pair lines, appear to be technically feasible and realizable at reasonable cost. None of them, however, are available in ready-made form for immediate installation. A development phase to develop sub-units which do not now exist, and then to assemble and test a sample system will be needed regardless of the system chosen.

Making a choice between these systems is not easy because such a choice should be based to some extent on factors which were not available during this study. One of the major factors concerns the availability of twisted-pair lines in the Merritt Island Complex. Cost estimates for the wired systems were made for the terminal equipment only, and with the assumption that existing lines could be used. If this is the case, it appears that a wired system can be implemented at a lower cost than a radio system. On the other hand, if new lines had to be installed the cost of a wired system would undoubtedly exceed the cost of a radio system.

Another factor which cannot be evaluated but which would affect consideration of a radio system is the requirement of radio silence during launch. Of the two radio systems, the X-band system appears more attractive from the viewpoint of both cost and the somewhat more advanced state-of-the-art in components. However, unless an X-band frequency authorization can be obtained, the X-band system must be dropped from consideration. Similarly, consideration of a 35 GHz radio system should anticipate whether or not transmission at 35 GHz will continue to be unrestricted.

Other factors which should be considered in addition to cost are reliability, maintainability, and expandability. These factors have not been studied in detail, but opinions can be given. A wired system using twisted-pair line would appear to offer greater reliability and less maintenance than a radio system. The reliability of the lines themselves cannot be approached by other transmission media. As for the terminal equipment, which is electronic in nature and not yet developed, the required circuitry is relatively simple and with proper design these components could be built to be highly reliable. Furthermore, the check-out and maintenance procedures should be relatively simple.

As for expandability, either system could be enlarged to add more events or more stations. The available bandwidth of the radio systems could easily accomodate more event signals. To make this capacity readily available, however, would require present anticipation of future needs and "overbuilding" of the initial system to provide more channels in the multiplexer, or sufficient transmitter power to drive additional antennas.

Alternatively, if a radio system were tailored precisely to the initial needs, expansion would require extensive modification or complete replacement.

On the other hand, expansion of the twisted-pair system would require only that additional terminal components be built and that additional lines (where needed) be provided. Since failure to anticipate future needs would not complicate the expansion at a future date, the twisted-pair system appears to offer somewhat more flexibility.

Considering all factors, it appears that if existing lines can be used, a system built around twisted-pair lines would be preferable in terms of lower initial cost, greater reliability, less maintenance, and easy expansion. Between the two wired systems, the one-event-per-line system could be implemented at a lower cost (excluding line costs) than the FDM system. However, the large number of lines required will probably make the FDM system more attractive. The main disadvantage of the FDM system appears to be the fact that multiplexing cannot be used on very long lines and, for a completely wired system, the one-line-per-event system would be required on paths with lengths exceeding about 15 miles.

Several other factors which are pertinent to the FDM twisted-pair system are:

(1) The sample system described in Section III was based on transmitting 30 events to 20 stations, with 5 stations in each of the four range categories. If the actual number of events to be transmitted is appreciably less than 30, the component cost should be markedly reduced.

(2) The modular nature of the system not only facilitates later expansion, but also makes it practical to implement a partial system now (less events, or less sites) and to enlarge it later as the need arises.

(3) If several sites exist at different points along a single cable, all of the sites might be served by a common set of pairs. The FDM input to each pair would have to be chosen to serve the most distant site. Intermediate sites could "pick-off" the signals from the lines. To do this would require that the event receivers have high impedance inputs, and it is recommended that they be so designed.

(4) Although detailed knowledge is not available on the nature of the events to be monitored, and the location of all sites to which signals are to be delivered, it is quite possible that all events need not be transmitted to all sites. If most of the sites need to monitor only a few events, a reduction in system cost and line requirements can be effected. Also, if only a few events will be meaningful at the most distant site, the use of one line for each required event may not be unattractive.

(5) If most of the events are needed at one or more sites whose distances forbid multiplex transmission over twisted pair, a small 35 GHz radio link might be used instead of using one-line-per-event. A modulation signal for the radio link could be obtained from the same multiplexer used for the wired system. For example, in the sample FDM system presented, the output of one of the 15 channel multiplexers could be heterodyned upward, filtered, and combined with the output of the other 15 channel unit to provide a 30 channel modulating signal. De-multiplexing equipment similarly could be built around two 15 channel receiver units.

It is recommended that the FDM system using twisted-pair lines be given serious consideration in selecting a system. If lack of sufficient lines or other factors rule this system out, a radio system would be the second choice. In the latter case, the choice between X-band and 35 GHz would have to be based primarily on whether an X-band channel can be authorized. Regardless of the system chosen, wired or wireless, it is recommended that a development phase be undertaken to design, build, and test a sample system.

VIII. Bibliography

1. G. S. Eager, I. Kolodny, L. Jachimowicz, and D. E. Robinson, "Transmission Properties of Polyethylene-Insulated Telephone Cables at Voice and Carrier Frequencies," Trans. AIEE, pt I, Vol. 78, November 1959, pp. 618-640.

2. F. E. Rogers, The Theory of Networks in Electrical Communication and Other Fields, MacDonald, London, 1957.

3. W. R. Bennett and J. R. Davey, Data Transmission, McGraw-Hill, New York, 1965.

4. Bell System Technical Staff, Transmission Systems for Communications, 3rd ed., Bell Telephone Laboratories, 1964.

5. K. W. Henderson and W. H. Kautz, "Transient Responses of Conventional Filters," Trans. IRE on Circuit Theory, Vol. CT-5, December 1958, pp. 333-347.

6. C. P. Eggen and A. S. McAllister, "Modern Low-Pass Filter Characteristics," Electro-Technology, August 1966.

7. E. Weber, Linear Transient Analysis, Vol. II, John Wiley & Sons, New York, 1956.